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A STATISTICAL COMPARISON OF DUFF SAMPLING TECHNIQUES, DUFF
AND PEAT MOSS MOISTURE RESPONSES UNDER ANALOGOUS CONDITIONS,
AND A MODEL OF ORGANIC HORIZON MOISTURE
RESPONSE TO SIMULATED RAIN EVENTS

by

Mary A. Smetanka

B.S., Montana State University, 1990

Presented in partial fulfillment of the requirements

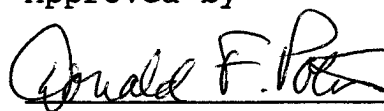
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Master of Science

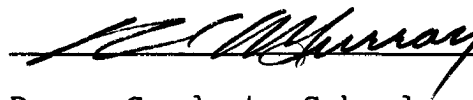
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A Statistical Comparison of Duff Sampling Techniques.....

Director: Donald F. Potts 

This thesis is composed of three separate investigations. Chapter One compares the destructive duff sampling and tray duff sampling measurement of forest duff under analogous climatic conditions. Chapter Two compares the moisture content response of forest duff and sphagnum peat moss under analogous climatic conditions. Chapter Three is a model of the response of organic horizon moisture content to simulated rain events. Each chapter constitutes a separate study. Thus, some introductory material and methodology is repeated in each chapter.

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CHAPTER ONE

Comparison of Duff Moisture Sampling Techniques: Destructive Sampling and Tray Sampling

ABSTRACT

In 1992, the effectiveness of destructive and tray duff moisture sampling techniques was evaluated. The destructive sampling method proved most effective when the duff mean gravimetric moisture content was below 100%. As the moisture content increased above 100%, the standard error exceeded 15%, and coefficient of variation exceeded 0.35. The tray weighing method was most effective at high moisture contents (>150%). Mean gravimetric moisture content and standard error were inversely related. The tray method was less variable at higher moisture contents. The tray collection method depicted wetting and drying cycles more distinctly than the destructive method. The tray method yielded mean moisture content measurements which were statistically similar to the destructive measurement in 19 of 25 instances. The destructive sampling method was most effective when measuring moisture contents during dry conditions, while the tray data technique was preferable when moisture contents exceeded 150%.

INTRODUCTION

Knowledge of duff moisture content is vital for wildfire behavior prediction, fire danger rating, and fire prescriptions. Two methods are used to determine duff gravimetric moisture content. The destructive samples method is common throughout United States. Canadian fire scientists use both the destructive sampling method and the

duff tray method.

The organic material deposited on the forest floor, generically referred to as duff, is a complex lattice containing organic material which has undergone varying degrees of humification. Humification involves oxidative and other chemical changes which results in the modification of chemical structure.

The litter layer is at the uppermost level in the duff horizon. Towbridge (1980) defines litter as "a terrestrial master organic horizon consisting of relatively fresh organic residues in which virtually entire original structures are discernable. [Litter] may be discolored and show some signs of biotic activity but is not substantially comminuted and does not show macroscopically obvious signs of deposition." The litter layer is typically composed of severed organic materials such as twigs, wood, and foliage (USDA SCS Soil Survey Staff, 1975).

The fermentation layer lies directly beneath the litter layer and is "a master organic horizon mostly characterized by disintegrated plant tissues in which partial, macroscopically discernable vegetative structures are dominant" (USDA SCS Soil Survey Staff, 1975). Materials composing this layer may be identified as to their origin. However, macromorphological decomposition is evident.

The humus layer lies directly above the uppermost mineral horizon and is "a terrestrial master organic horizon

dominated by fine substances in which the original structures are macroscopically indiscernible" (USDA SCS Soil Survey Staff, 1975). The humus layer may be composed entirely of organic matter, or a combination of mineral and organic materials. The humus layer is noted for its inherent variability as well as for thicknesses and sequences that can change abruptly (Klinka et al., 1981).

For the purpose of this study, duff consists of three layers, Oi (litter layer), Oe (fermentation layer), and Oa (humus layer), as defined by the USDA SCS Soil Survey Staff (1992).

The destructive sampling method requires removal of a sample which damages the structural integrity of the organic complex. The tray weighing method involves carefully removing a series of intact organic horizons (monoliths), placing them in wire mesh baskets, and restoring them to their original locations. Tray weighing suffers from artificiality because the mineral soil-duff interface is disturbed, and duff does not remain in its "true" environment (Van Wagner, 1983).

In the only reported study comparing the two duff moisture sampling methods, Van Wagner (1983) concluded that the destructive method yields more accurate measures of duff moisture content (Van Wagner, 1983). The variance found in the destructive technique is large enough that an adequate number of samples must be removed to reduce the standard

error to an acceptable level. Due to the variance in destructive sample population, trends in moisture content change are better assessed with the tray weighing method (Van Wagner, 1983). Van Wagner (1983) also recommended that both methods be used concurrently to cover all sampling facets to better describe the error in each method.

The objective of this study was to validate assertions made by Van Wagner (1983) by comparing the two methods under analogous field conditions and determine whether both yield statistically similar measures of mean moisture content, and to suggest conditions which may maximize the effectiveness of either technique. If the tray weighing method produces gravimetric moisture values that are statistically similar to the destructive sampling method, then perhaps the tray weighing method is the most effective sampling method because it can provide accurate information regarding both absolute moisture content and its fluctuation.

METHODS

Study Sites

One hectare study sites were located on the University of Montana's Lubrecht Experimental Forest and on the Superior Ranger District of the Lolo National Forest. The sites were clearcut in the spring of 1992. Great care was taken to insure minimal disturbance of the duff on each site during

harvest activities. The Lubrecht site was on a southern exposure in the Lubrecht Experimental Forest (T13N R14W S12 SW $\frac{1}{4}$ NE $\frac{1}{4}$) at an elevation was 1855m and an estimated annual precipitation of 50cm. The timber stand composition was predominantly 90 year-old lodgepole pine (Pinus contorta) with few co-dominant Douglas-fir (Pseudotsuga menziesii).

The Hagan study site, 10km north of Hagan, Montana (T19N R30W S07 NE $\frac{1}{4}$ NE $\frac{1}{4}$), was a west aspect at an elevation of 1190m and averaged 102cm of precipitation annually. The 100+ year-old stand consisted of western red cedar (Thuja plicata), western larch (Larix occidentalis), grand fir (Abies grandis), and Engelmann spruce (Picea engelmannii). Duff thickness at both sites was compared against a previously cataloged set of species-dependent duff thicknesses (Brown and See, 1981) to ascertain that the experimental population was representative of typical duff thicknesses in western Montana.

Data Collection

Duff monoliths measuring 8 in x 8 in (64 in²) were carefully removed from the forest floor using a flat blade shovel. The duff-mineral soil interface was carefully scraped to remove as much mineral material as possible. Monolith thicknesses varied, as did the natural duff thickness at each site. The monoliths were placed in 8 in by 8 in wire mesh baskets lined with fine nylon mesh to

minimize organic matter loss (Alexander et al., 1991).

There were 13 monoliths on the Haugan site and 5 on the Lubrecht sites. Sample size was limited at the Lubrecht site because rockiness permitted removal of few intact organic horizons. Moisture sampling times and intervals were weather dependent. The sampling goal was to measure moisture contents immediately before a wetting event and during the subsequent drydown. A Remote Automated Weather Station (RAWS) located near the Haugan site was used to schedule data collection. Because the Haugan site had a larger sample size, and superior sampling timing, data from the Lubrecht site was considered secondary. The recommendation of ten or more samples from the mesic zone (Potts et al., 1986) was followed when determining duff-tray locations and initiating the destructive sampling regime.

The tray-duff was weighed on-site with a spring balance. Immediately afterward replicates destructive samples were placed in soil sample cans and sealed with tape for transport to the lab.

Analysis

Standard methods were used to determine the gravimetric moisture content of all samples. Destructive sample oven dried weights (ODW) were determined immediately after sampling. Tray sample ODW were not determined until the end

of the field season. This was because exposure to extreme heat may affect the structural properties of duff which in turn may alter duff water retention properties. The use of gravimetric moisture content was preferred over volumetric moisture content because of the extreme variability of bulk density in organic horizons.

RESULTS AND DISCUSSION

During the sampling period, 381 destructive samples were removed from the Haugan site generating an average error of 4.2 % at $\alpha = 0.05$. The average error margin of the Lubrecht destructive data was 8.8% at $\alpha = 0.05$. The average percent error ($\alpha = 0.05$) for the tray data collection at the Haugan and Lubrecht study sites was 3.3% and 4.9%, respectively (Table 1.1).

Table 1.1 Sample size and sample error data from the Haugan and Lubrecht study sites.

LOCATION	TYPE	ERROR(%)	N
Haugan	destructive	4.2	381
Haugan	tray	3.3	287
Lubrecht	destructive	8.8	61
Lubrecht	tray	4.9	30

The two sample t-test ($\alpha = 0.05$), as defined by Moore and McCabe (1989), was used to test the null hypothesis:

$$H_0: \theta_t = \theta_d$$

$$H_1: \theta_t \neq \theta_d$$

Two sample t-test statistic:

$$t = (\theta_t - \theta_d) / (s_p) * ((1/n_t) + (1/n_d))^{1/2}$$

Where the pooled standard deviation (s_p) was defined as:

$$s_p^2 = ((n_t - 1) * s_t^2 + (n_d - 1) * s_d^2) / (n_t + n_d - 2)$$

Where the variables were:

θ_t = tray mean

θ_d = destructive mean

s_t = tray standard deviation

s_d = destructive standard deviation

n_t = number of tray samples

n_d = number of destructive samples

The null hypothesis was rejected on 2 of 4 tests at the Lubrecht site and on 4 of 21 tests at the Haugan site. Fifty percent of the null hypothesis rejections, at both sites, occurred when the destructive method recorded lower mean gravimetric moisture contents than the tray method. At the Haugan site, the two methods produced significantly different results on days (Julian) 190, 210, 230, and 244

(Table 1.2). Also, three of the four null hypothesis rejections at the Haugan site occurred when a mean moisture content less than 100% was measured by one of the methods. Both rejections of the null hypothesis at the Lubrecht site occurred when θ_d was less θ_t (Table 1.3).

Table 1.2 Haugan site moisture content results where θ_t is the mean tray moisture content, s_t is the tray standard deviation, θ_d is the mean destructive moisture content, and s_d is the destructive standard deviation.

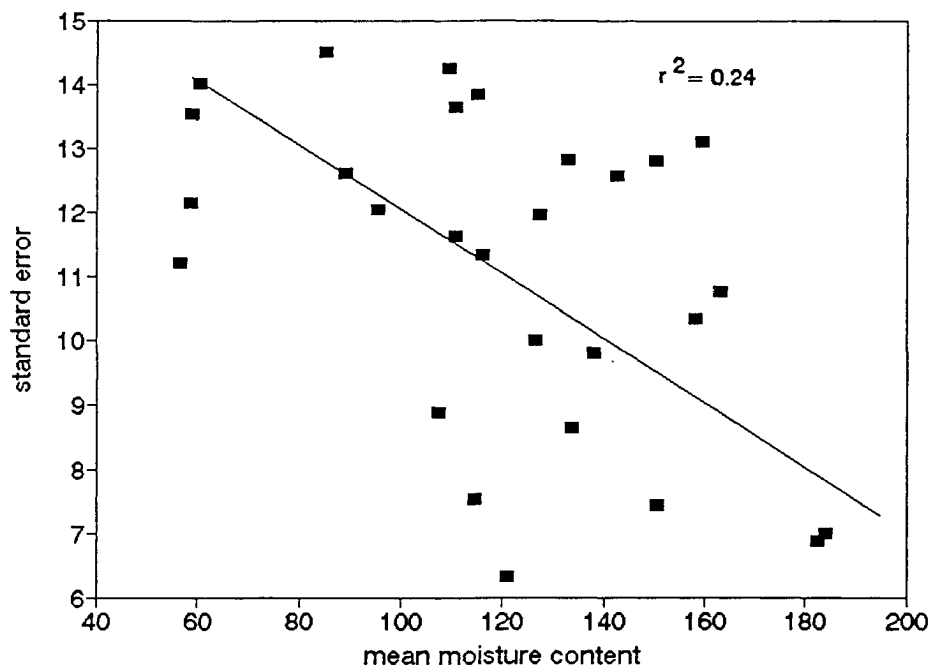
DAY	θ_t	s_t	θ_d	s_d	t	REJECT
133	130	26	115	25	-1.36	n
141	140	36	151	25	0.77	n
149	145	56	107	29	-1.95	n
163	104	41	115	31	0.52	n
165	126	54	158	34	1.60	n
170	108	32	116	38	0.50	n
172	99	34	95	40	-0.20	n
176	79	22	59	40	-1.32	n
183	138	46	163	36	1.38	n
190	103	32	184	34	6.41	y
197	126	35	127	43	0.07	n
200	83	33	89	46	0.41	n
202	144	69	143	45	-0.05	n
210	70	21	109	51	2.53	y
230	138	90	60	50	-2.65	y
237	106	37	121	17	1.03	n
240	82	18	111	49	1.94	n
244	38	6	85	52	3.19	y
250	103	38	126	59	1.07	n
254	114	50	133	46	1.04	n
289	116	36	111	42	-0.48	n

Table 1.3 Lubrecht Site Moisture Results where, θ_t is the mean tray moisture content, s_t is the tray standard deviation, θ_d is the mean destructive moisture content, and s_d is the destructive standard deviation.

DAY	θ_t	s_t	θ_d	s_d	t	REJECT
187	134	47	130	32	0.18	n
194	68	38	70	26	-0.11	n
203	121	29	77	32	2.75	y
234	178	21	56	11	12.20	y

The tray data standard error (SE) ranged from 6 to 19% (Fig. 1.1). The SE ranged from 11 to 14.5 % when the θ_i was between 50 % and 100 %. Once θ_i exceeded 100% the low end of the SE range dropped to 6%.

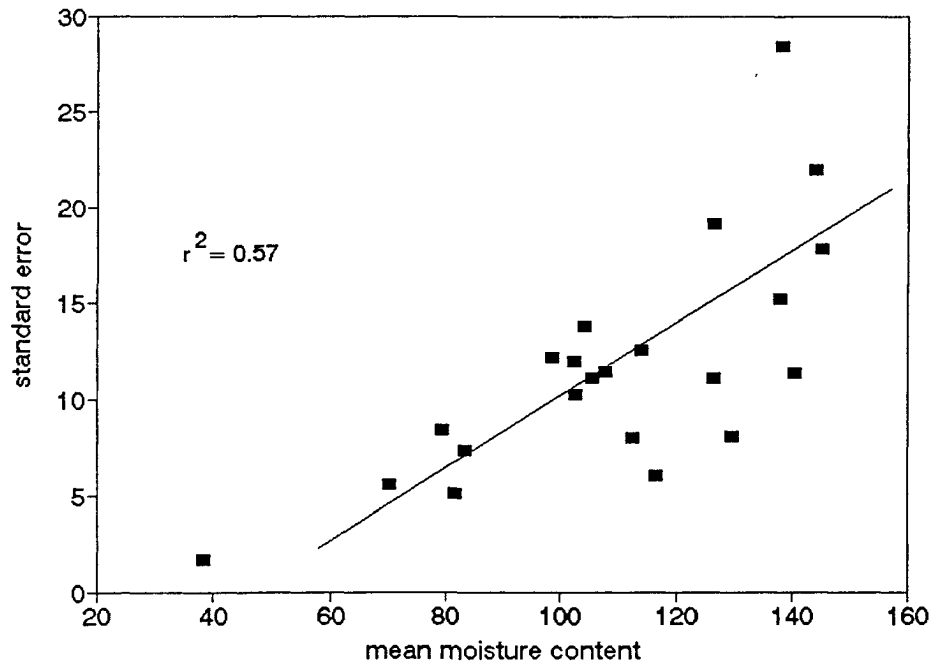
Figure 1.1 Relationship between θ_i (mean moisture content determined by the tray sampling method) and standard error at the Haugan study site.



The SE for the destructively sampled data varied over a wider range (2%-30%) than that of tray data (Fig 1.2). Also, the SE was much smaller at the lower moisture contents (eg. 2% SE when θ_d is 40%). Unlike the tray data, θ_d and SE were directly proportional. When θ_d exceeded 135%, the SE ranged from 12%-28%. Yet, when θ_d was between 75% and

120%, the SE varied from 5% to 17%.

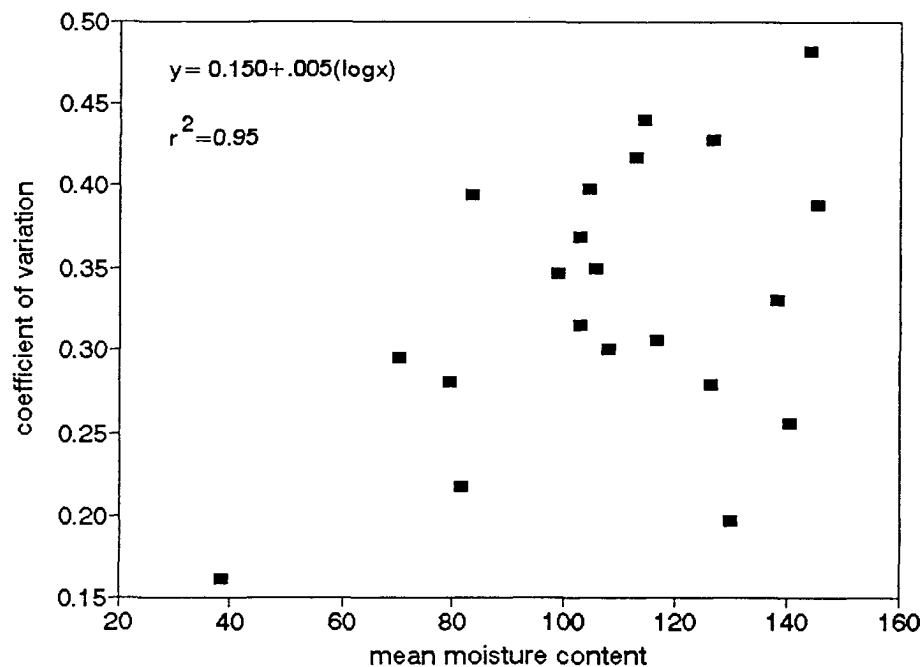
Figure 1.2 Relationship between θ_d (mean moisture content determined by the destructive sampling method) and standard error at the Haugan study site.



The relationships between the mean gravimetric moisture content and the coefficient of variation (CV) for the two sampling techniques were opposite. The CV increased for the destructive sampling technique as θ_d increased (Fig. 1.3). The behavior of the CV with reference to the θ_d fits the following equation ($x = \theta_d$ and $y = CV$).

$$y = 0.14999 + 0.00478 (\log x) \quad r^2 = 0.95$$

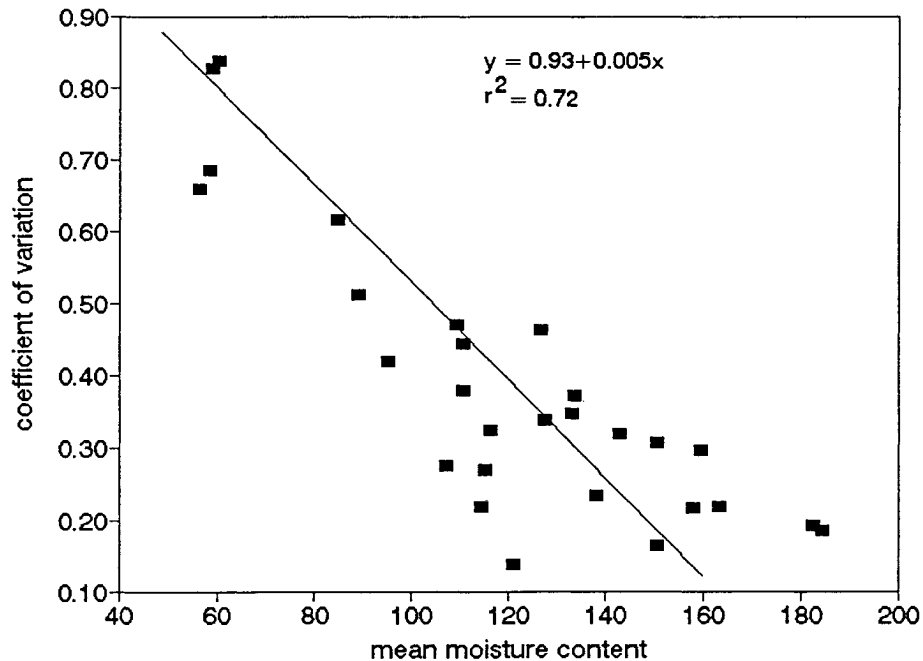
Figure 1.3. The relationship between θ_d and coefficient of variation at the Haugan study site using the destructive sampling method.



In contrast, for tray samples, CV and θ_i were inversely proportional (Fig. 1.4). The response of the CV with respect to θ_i conforms to the following equation ($x = \theta_i$ and $y = CV$).

$$y = 0.9299 - 0.00456 (x) \quad r^2 = 0.72$$

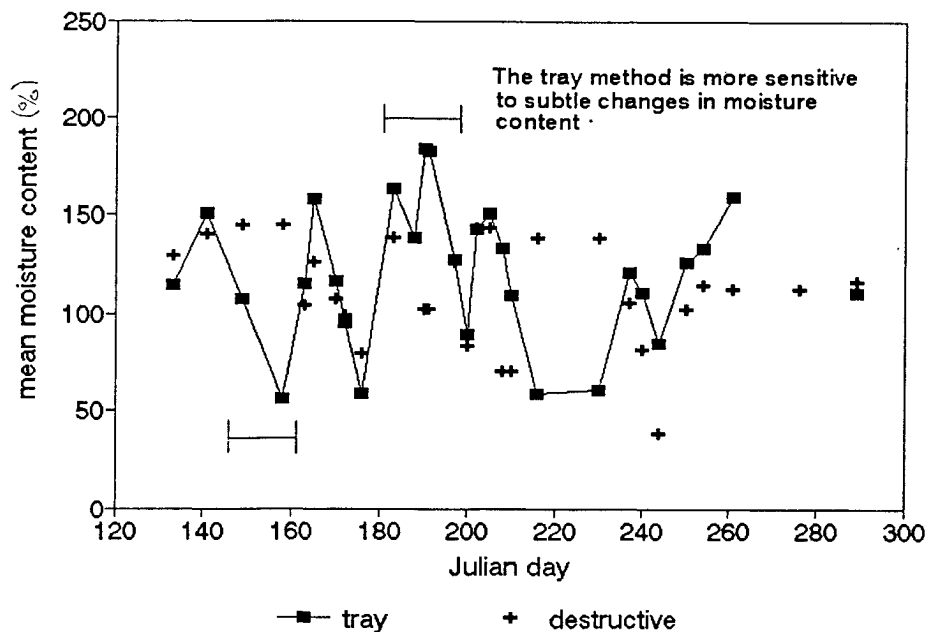
Figure 1.4 Relationship between θ_i and coefficient of variation at Haugan study site using the tray sampling method.



The tray weighing technique was more sensitive than destructive sampling for capturing the response of duff to change in environmental conditions. The tray duff depicted responses of greater magnitude to both wetting and drying events. During a forty-day period (Fig. 1.5) the tray duff data revealed two wetting-drying cycles which the destructive sampling failed to detect. However, the more

dynamic response may be attributed to the artificial environment created by the wire baskets.

Figure 1.5 Daily mean moisture contents at the Haugan study site using both duff moisture sampling methods.



There were several advantages and disadvantages for both techniques. The duff tray method was most effective when the mean gravimetric moisture content was greater than 100%. Destructive sampling was more effective when the duff was drier. Neither method was superior over the full range of moisture contents sampled. Destructive method had a much

lower coefficient of variation (0.65) at higher moisture contents than the tray technique at lower moisture contents (0.9). From the standpoint of variation, the destructive method outperformed the tray method over ranges where it was not the theoretically optimal method. In future studies, if the sensitivity to moisture change is a desired sampling characteristic, the tray method may prove optimal.

The duff-tray gravimetric moisture contents were similar to the destructive samples in 76% of the comparisons. For the tray method, standard error was fairly consistent over the range of recorded moisture contents, and the coefficient of variation decreased as the mean moisture content increased (Figures 1.1 and 1.4). The tray method was particularly effective when moisture contents were in excess of 120%.

The destructive method appeared more suitable for drier sites. The standard error at mean moisture contents of 40% and 100% were 2% and 13%, respectively. As the mean moisture content increased, the standard error and the coefficient of variation also increased. When the mean moisture content was 140%, the standard error exceeded 20%. The number of samples required to bring error within acceptable ranges is a limitation of the destructive sampling method. In future studies, the destructive method which required no site preparation may be the method of choice if data needs change on short notice.

CONCLUSIONS

Some of Van Wagner's (1983) statements were corroborated by this study. The tray method appeared to provide superior information regarding trends in moisture condition.

However, the mean gravimetric moisture contents determined by both methods were statistically similar during 76% the comparisons, with the destructive method being most effective at lower moisture contents.

The difference in effectiveness between the two techniques may have resulted from the artificial environment of the duff trays. Stocks (1970) determined that a high percentage of moisture actually reaches the duff layer nearest the soil and considerable amounts infiltrate into mineral soil. Although untested, Stocks (1970) suggested that the mineral soil draws the moisture downward through the lower duff layers but the transport mechanism was unknown. The wire trays created a minimum break of approximately 0.5cm between the mineral soil horizon and the duff sample. The organic horizon-mineral horizon interface was substantially disturbed during the tray method sample preparation.

An artificial environment was created which may have adversely effected the ability of the Oa layer to transmit moisture into the mineral horizon. Although the mean moisture contents from both methods are statistically similar, the tray means tended to be slightly higher than those measured with destructive sampling. The tray moisture

contents may have been higher because the tray duff was unable to transmit moisture into the soil. If the ability for the organic horizon to transmit moisture into the mineral horizon is disturbed, evaporation becomes the dominant mechanism for moisture loss during the drydown phase. Evaporative drying becomes less effective as moisture moves deeper into the soil horizon. Fifty percent (3 of 6) of the null hypothesis rejections occurred when the tray mean exceeded the destructive mean or when the destructive mean was nearing the low point of the drydown cycle. As the duff dries, the tray weighing method become less accurate and more variable.

The increase of variation with decreasing mean moisture content may be attributed to the nonuniformity of the tray samples. When the samples were prepared some fit into the trays exactly, whereas others had to be modified. The organic horizon-mineral soil interface was irregular as opposed to optimally being flat and symmetrical). The amount of suitable soil interface varied by sample. When the duff is wet there may be enough moisture present to allow transmission at rates similar to that of undisturbed organic material. As duff dries, less moisture is available and the transmission process may be affected to a degree that moisture transmission occurs only through optimal soil/duff interface areas.

There are inherent advantages and disadvantages to both

sampling techniques. The simultaneous use of both sampling techniques to cover all possible conditions and data needs would be ideal. However, when not practical, a decision to use either method must be made based upon data needs and duff moisture conditions.

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CHAPTER TWO

A Comparison of Duff and Peat Moisture Contents Under Analogous Field Conditions

ABSTRACT

This study examines the moisture content response of forest floor duff and commercial peat moss under analogous climatic conditions to determine if the peat moisture content behaves similarly to that of duff. Statistically, the results indicate that peat and duff behave similarly ($\alpha=.05$). However, a component of the peat population responded erratically, causing a large variance (s^2) when performing the statistical analysis. A peat sample placed in a wet, sheltered area often contained 2 to 3 times more moisture than either the duff or the other peat samples. Peat plots placed in characteristic locations tended to have slightly lower moisture contents than the duff. After removing the erratically behaving peat sample, analysis indicated that the gravimetric moisture content of sphagnum peat moss is statistically similar to that of duff no more than 50 % of the time.

INTRODUCTION

Duff moisture content knowledge is vital for fire management decisions such as predicting wildfire behavior, fire danger rating, and fire prescription formation. Commercial peat moss is not routinely used as a duff substitute for mean gravimetric moisture content (θ) estimations, despite being readily available and easy to

work with. Data comparing peat and duff moisture properties is not available.

The organic material deposited on the forest floor is a complex lattice containing material which has undergone varying degrees of humification. Humification involves oxidative and other chemical changes which result in the subsequent modification of the duff chemical structure.

The duff litter layer is located at the uppermost level in the horizon. Towbridge (1980) defines litter as 'a terrestrial master organic horizon consisting of relatively fresh organic residues in which virtually entire original structures are discernable. [Litter] may be discolored and show some signs of biotic activity but is not substantially comminuted and does not show macroscopically obvious signs of deposition.' The litter layer is typically composed of severed organic materials such as twigs, wood, and foliage (Soil Survey Staff, 1975).

The fermentation layer lies directly beneath the litter layer. The Soil Survey Staff (1975) defines the fermentation layer as 'a master organic horizon characterized by more-or-less disintegrated plant tissues in which partial (rather than entire), macroscopically discernable vegetative structures are dominant'. Materials composing this layer may be identified to their origin, but macromorphological decomposition is evident.

The humus layer lies directly above the uppermost mineral

horizon. The Soil Survey Staff (1975) defines the humus layer as 'a terrestrial master organic horizon dominated by fine substances in which the original structures are macroscopically indiscernible'. The humus layer may be composed of entirely organic material or both mineral and organic materials. The humus layer is noted for its inherent variability as well as for thicknesses and sequences that can change abruptly (Klinka et al., 1981).

For the purpose of this study, duff consists of three layers Oi (litter layer), Oe (fermentation layer), and Oa (humus layer), as defined by the Soil Survey Staff (1992).

The destructive sampling and *in situ* weight measurement method involved removing a segment of duff in a manner which damages the structural integrity of the sample. The tray technique involved carefully removing a series of intact organic horizons (monoliths), placing them in wire mesh baskets, and replacing them to their original locations. Tray weighing suffers from artificiality because the organic horizon-mineral horizon interface was disturbed and therefore, duff does not remain in its "true" environment (Van Wagner, 1983). The destructive method yielded more accurate moisture content measurement (Van Wagner, 1983). But, trends in moisture content change were better acquired by tray weighing (Van Wagner, 1983). Van Wagner (1983) also recommended concurrent use of both methods to cover all possible conditions.

The study objective is to determine if peat moisture content behaves similarly ($\alpha = .05$) to duff moisture content under analogous climatic conditions. The peat mean gravimetric moisture content (θ_p) will be compared to duff mean gravimetric moisture content measured by destructive sampling (θ_d) and tray weighing techniques (θ_i).

METHODS

Study Sites

One hectare study sites were located on the University of Montana Lubrecht Experimental Forest and on the Superior Ranger District of the Lolo National Forest. The sites were clearcut in the spring of 1992. Great care was taken to insure minimal disturbance of the duff on each site during harvest activities. The Lubrecht study site was on a southern exposure in the Lubrecht Experimental Forest (13N R14W S12 SW $\frac{1}{4}$ NE $\frac{1}{4}$) at an elevation of 1855m and an estimated annual precipitation of 51cm. Timber stand composition was predominately 90-year-old lodgepole pine (Pinus contorta) with few co-dominant Douglas-fir (Pseudotsuga menzeisii).

The Haugan study site, 10 km north of Haugan, Montana (T19N R30W S07 NE $\frac{1}{4}$ NE $\frac{1}{4}$) was a west aspect at an elevation of 1190m and averaged 102 cm of precipitation annually. The 100+ year-old stand consisted of western red cedar (Thuja plicata), western larch (Larix occidentalis), grand fir (Abies grandis), and Engelmann spruce (Picea engelmanni). Duff thickness at both sites was compared against a

previously cataloged set of species dependent duff thicknesses (Brown and See, 1981) to verify that the experimental population was representative of typical duff depths.

Data Collection

Each site contained a set of duff monoliths, in trays, and a set of tray peat samples. Trays were constructed of rigid hardware cloth and lined with fine nylon mesh to minimize organic material loss, as presented by Alexander et al. (1991). The trays were 64 in². Monolith thickness varied depending on duff thickness and the desired peat thickness.

Duff monoliths measuring 8 in by 8 in were carefully removed, organic profile intact, with a flat blade shovel. The mineral material existing at the organic-mineral soil interface was carefully removed to minimize the mineral material content. Duff samples were placed in trays and positioned on the site. The Lubrecht site sample size was limited because the rockiness prevented removal of many intact duff horizons. The Lubrecht site data value was secondary to the data from the Haugan site, which was sampled more intensively.

Peat moss was placed in trays and located in excavated forest floor cavities. Prior to measurement, peat samples were allowed several weeks the peat to settle and for moisture content equilibration to local conditions. Peat

sample bulk density approximated typical duff bulk densities.

Duff moisture may vary considerably within a site, particularly in steep or irregular terrain (Potts et al, 1986). Since simple random sampling often requires 40 or more observations to secure the desired error, stratified random sampling was used because it provided reliable estimates with less time and effort. Convex and concave areas tend to be relatively dry and wet, respectively, while areas between topographic extremes tends to have a mesic, or intermediate, moisture regime. The mid-slope stratum displays the greatest variation in duff moisture while the ridges and draws tend to be more uniformly dry and wet. Recommendations of ten or more samples from the mesic zone by Potts et al.(1986) were followed when determining monolith location and when initiating the destructive sampling regime. The sampling regime was based on the needs of an associated project (Smetanka, 1993) As a consequence, the sites were sampled prior to anticipated rain events and immediately thereafter to acquire data from the ensuing drydown.

Soil-sample cans were used for the destructive data collection. Lids were sealed with tape to prevent moisture loss during transport. The samples were weighed for wet weight measurements. The samples were heated to 105° C until a constant weight was reached (Ponto, 1972). The

samples were weighed again and the oven dry weight (ODW) was recorded. The gravimetric moisture content (θ) was determined using the following formula:

$$\theta = ((\text{wet weight} - \text{ODW}) / \text{ODW}) \times 100$$

ODW for both the duff monoliths and the peat were not determined until the end of the field season. Heat exposure (105°) may have affected organic matter structural properties which may have influenced the water retention characteristics.

RESULTS AND DISCUSSION

The average percent error of the sampling regime at the Haugan site averaged 4.2%, 3.3%, and 20.9% for destructively sampled duff, tray duff, and peat moss, respectively (Table 2.1). Sampling error at the Lubrecht site for destructively sampled duff, tray monoliths, and peat averaged 8.8%, 4.9%, and 12.0%, respectively (Table 2.1).

Table 2.1. Sample size and sample error data at the Haugan and Lubrecht study sites.

Location	Type of sample	error(%)	N
Haugan	duff-destructive	4.2	381
Haugan	duff-tray	3.3	287
Haugan	peat	20.9	71
Lubrecht	duff-destructive	8.8	61
Lubrecht	duff-tray	4.9	30
Lubrecht	peat	12.0	10

Two sets of hypothesis were tested. Set one tested if the mean moisture contents of peat moss (θ_p) and duff measured by the tray method (θ_t) were equal. Set two tested if the mean moisture content of peat moss and destructively sampled duff (θ_d) were equal. The two sample t-test was used to test the null hypothesis at $\alpha = 0.05$.

Set 1

$$H_0: \theta_t = \theta_p$$

$$H_1: \theta_t \neq \theta_p$$

Set 2

$$H_0: \theta_d = \theta_p$$

$$H_1: \theta_d \neq \theta_p$$

Two sample t-test statistic:

$$t = (\theta_d - \theta_p) / (s_p) * ((1/n_p) + (1/n_d))^{1/2}$$

$$s_p^2 = ((n_p - 1) * s_p + (n_d - 1) * s_d) / (n_p + n_d - 1)$$

θ_p = mean - peat

θ_d = mean - destructive method

s_p = standard deviation - peat

s_d = standard deviation - destructive method

n_p = number of samples - peat

n_d = number of samples - destructive method

The set one null hypothesis was rejected on 2 of 24 attempts at the Haugan site (Table 2.2) and on 2 of 5 attempts at the Lubrecht site (Table 2.3). The high degree of variance within the Haugan peat data contributed to the failure to reject the set one null hypothesis. Three peat samples were located at Haugan. The moisture content of samples 1 and 3 (Figure 1.1) behaved similarly throughout the sampling period while sample 2 moisture content did not. From days 175 through 205, the sample 2 moisture content pattern differed from the rest of the population. From days 205 through 237, sample moisture content decreased considerably (from 375% to 200%). The moisture content of Sample 2 was typically double that of the other peat samples.

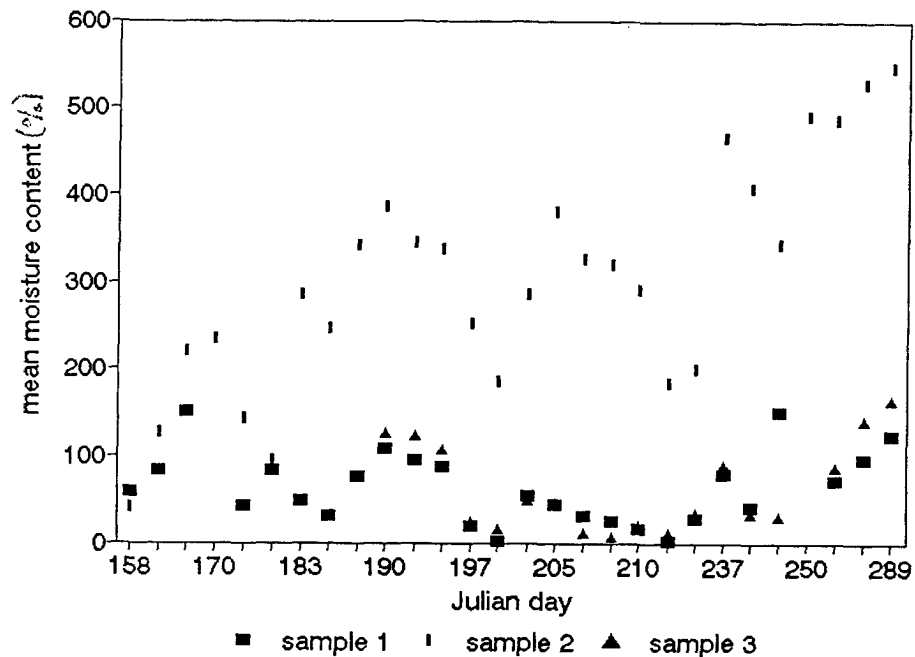
Table 2.2. Haugan site peat and duff mean moisture content results, standard deviation(s), and t-values using the tray sampling method.

day (j)	θ_i	s_i	θ_p	s_p	t	reject
158	56	37	50	12	0.24	n
163	115	31	106	30	0.36	n
165	158	34	186	49	-0.99	n
170	116	38	249	--	-4.33	y
172	95	40	92	72	0.07	n
176	59	40	90	8	-1.05	n
183	163	36	167	168	-0.08	n
188	138	33	158	152	-0.49	n
190	184	34	208	145	-0.74	n
191	183	35	198	132	-0.52	n
197	127	43	99	134	0.69	n
200	89	46	68	102	0.58	n
202	143	45	130	135	0.31	n
205	150	46	157	194	-0.12	n
208	134	49	140	157	-0.16	n
210	109	51	109	158	-0.00	n
216	59	49	66	102	-0.18	n
230	60	50	87	97	-0.71	n
237	121	17	212	220	-1.18	n
240	111	49	161	214	-0.84	n
244	85	52	175	158	-1.82	n
254	133	46	214	236	-1.29	n
261	160	47	255	238	-1.50	n
289	111	42	277	234	-2.71	y

Table 2.3. Lubrecht site peat and duff moisture contents, standard deviation(s), and t-values using the tray sampling method.

day (j)	θ_i	s_i	θ_p	s_p	t	reject
187	134	47	72	10	2.80	y
194	68	38	29	8	2.17	n
203	121	29	111	13	0.63	n
215	24	20	19	3	0.54	n
234	178	21	222	3	-4.57	y

Figure 2.1. Depiction of Haugan site peat sample moisture content during the 1992 field season.



The set two null hypothesis was rejected on 4 of 17 attempts at Haugan (Table 2.4), and on 3 of 4 attempts at Lubrecht (Table 2.5). Irregular behavior of peat sample 2 resulted in very large standard deviations and contributed substantially to t-values which rendered the differences statistically insignificant.

Table 2.4 Haugan site peat and duff moisture content data, standard deviation (s), and t-values using the destructive sampling method.

day(J)	θ_d	s_d	θ_p	s_p	t	reject
163	104	41	106	30	-0.06	n
165	126	54	186	50	-1.49	n
170	108	32	249	--	-5.31	y
172	99	34	93	72	0.19	n
176	79	22	90	9	-0.61	n
183	138	46	167	168	-0.53	n
190	103	32	208	145	-2.34	y
197	126	35	99	134	0.63	n
200	83	33	68	102	0.56	n
202	144	69	130	135	0.25	n
210	70	21	109	157	-0.97	n
230	138	90	87	97	0.85	n
237	106	37	212	220	-1.70	n
240	82	18	160	214	-1.43	n
244	38	6	175	158	-3.54	y
254	114	50	215	236	-1.71	n
289	116	36	278	234	-4.17	y

Table 2.5. Lubrecht site duff and peat moisture data, standard deviations (s), and t-values using the destructive sampling method

day (J)	θ_d	s_d	θ_p	s_p	t	reject
187	130	32	72	10	3.60	y
194	70	26	29	8	3.40	y
203	77	32	111	13	1.99	n
234	56	11	222	3	36.60	y

Sample 2 was treated as an outlier and excluded from the following analysis, which is identical to hypothesis sets 1 and 2, respectively.

Set 3

$$H_0: \theta_d = \theta_p$$

$$H_1: \theta_d \neq \theta_p$$

Set 4

$$H_0: \theta_t = \theta_p$$

$$H_1: \theta_t \neq \theta_p$$

Two sample t-test statistic:

$$t = (\theta_d - \theta_p) / (s_p) * ((1/n_p) + (1/n_d))^{1/2}$$

$$s_p^2 = ((n_p - 1) * s_p + (n_d - 1) * s_d) / (n_p + n_d - 1)$$

θ_p = mean - peat

θ_d = mean - destructive method

s_p = standard deviation - peat

s_d = standard deviation - destructive method

n_p = number of samples - peat

n_d = number of samples - destructive method

The set 3 null hypothesis was rejected on 4 of 11 attempts, and the set 4 hypothesis was rejected on 7 of 16 attempts (Table 2.6). The primary effect of the omission of Sample was the decreased variance, which contributed directly to higher t-values.

Table 2.6. Haugan Site t-test results when discounting sample 2

day	t	reject null	t	reject null
190	-0.55	n	2.35	y
191	--	-	2.81	y
197	1.11	n	1.26	n
200	3.12	y	3.18	y
202	1.81	n	3.56	y
205	--	-	3.34	y
208	--	-	3.44	y
210	3.44	y	2.75	y
216	--	-	1.54	n
230	1.62	n	0.79	n
237	0.76	n	0.94	n
240	3.39	y	2.06	n
244	-2.81	y	-0.14	n
254	0.96	n	1.50	n
261	--	-	1.07	n
289	-1.05	n	-0.96	n

The non-typical behavior of Sample 2 was thought to be a function of location. Its location was in a damp, sheltered area which received limited direct sunlight.

A previous study (Smetanka, 1993) indicated that both destructively sampled duff and tray sampled duff had statistically similar moisture contents under analogous field conditions. Tray data often measured higher (but not statistically significant) moisture contents than the destructive method. Peat moisture content, without Sample 2, was frequently less than duff moisture measured by either method (Figure 2.2). The mean peat moisture content of Samples 1 and 3, was less than when the entire peat population mean (Figure 2.3).

Figure 2.2. Mean daily moisture contents of the entire peat population and duff measured by both methods.

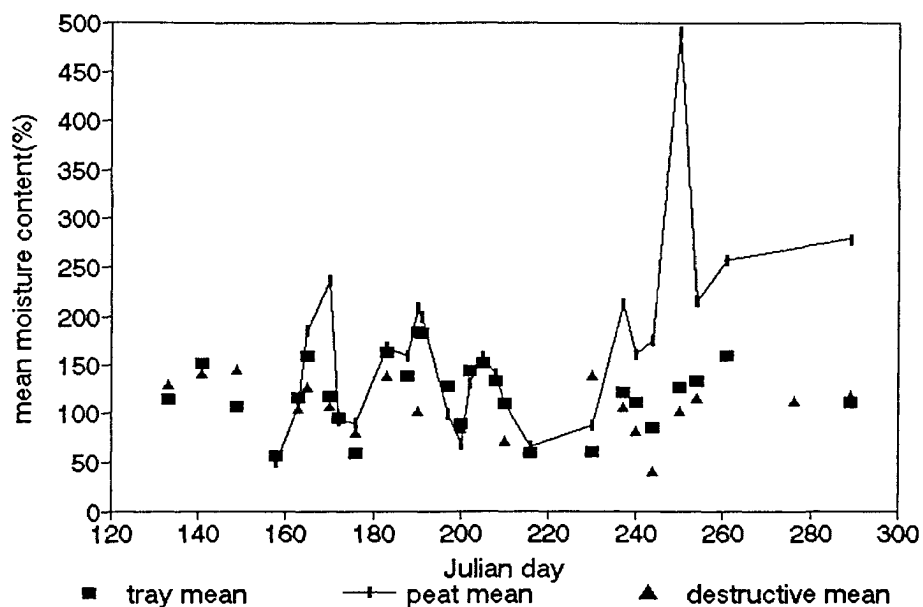
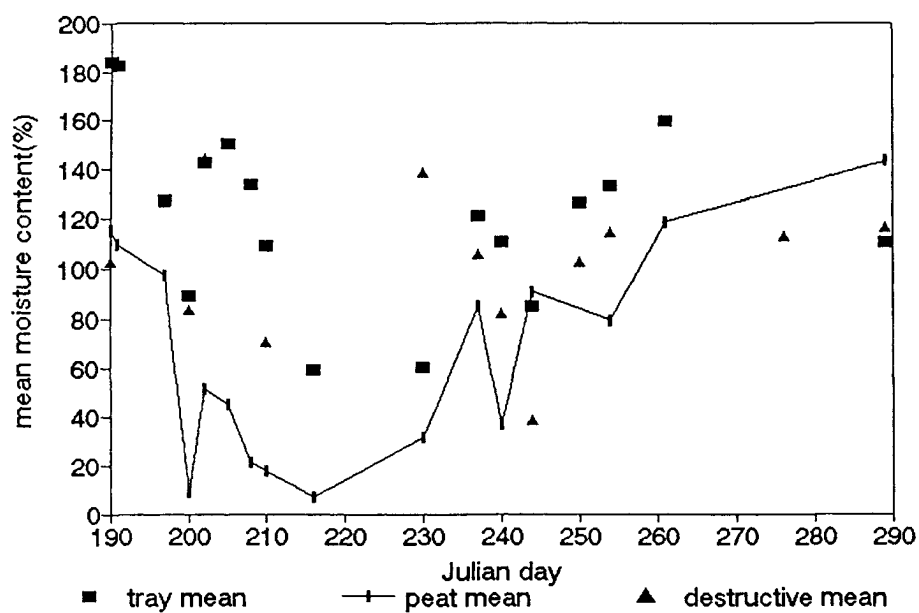


Figure 2.3. Mean daily moisture contents of destructively sampled duff, tray sampled duff, and the trimmed peat population.



CONCLUSIONS

Variation within the peat population contributed to the inability to reject claims that peat and duff moisture content behave similarly under analogous conditions. The peat population variability was significantly affected by placement of a peat sample in an unknown wet area. Other peat samples behaved similarly throughout the field season.

When omitting the erratic peat sample, variability in the peat population decreased considerably. Statistical analysis resulted in evidence that the peat moisture content behaved similarly to duff moisture no more than 60 % of the time. Based on these results, peat suitability as a duff surrogate is questionable.

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CHAPTER THREE

A model of the response of organic horizon moisture content to simulated rain events

ABSTRACT

Rain simulations on western Montana forest duff monoliths were conducted to construct a model predicting post-storm gravimetric moisture content. Selected duff and storm characteristics were incorporated into the model. The model r^2 was 0.80. Pre-storm duff moisture content was the most significant variable ($t = 32.42$). Precipitation depth and duff thickness also significantly influenced the model outcome. Storm duration was not a significant factor. The effects of selected storm and duff characteristics were studied to determine their relationship to percent water retention and overall water gain. Percent moisture retention was negatively related to the pre-storm moisture content. Percent retention was positively related to duff thickness, but inversely related to precipitation depth. A second model with the same parameters was constructed using commercial sphagnum peat moss monoliths.

INTRODUCTION

Knowledge of the dynamics of duff moisture is vital for fire management decisions such as wildfire behavior prediction, danger rating, and fire prescription formation. The Priestley-Taylor (P-T) duff moisture model uses data computed by the P-T Potential Evaporation Model to determine the drying rates of forest duff. The P-T duff moisture

model utilizes an algorithm for estimating post wetting duff moisture. The model estimates that the organic horizon retains 20% of the precipitation that it receives (Stocks, 1970). Storm characteristics and duff properties were not factored into the 20% retention estimate.

The organic material deposited on the forest floor, generically referred to as duff, is a complex lattice containing organic material which has undergone varying degrees of humification. Humification involves oxidative and other chemical changes which result in modification of the chemical structure.

The duff litter layer is located at the uppermost level in the organic horizon. Towbridge (1980) defines litter as 'a terrestrial master organic horizon consisting of relatively fresh organic residues in which virtually entire original structures are discernable. [Litter] may be discolored and show some signs of biotic activity but is not substantially comminuted and does not show macroscopically obvious signs of deposition.' The litter layer is typically composed of severed organic materials such as twigs, wood, and foliage (Soil Survey Staff, 1975).

The fermentation layer lies directly beneath the litter layer. The Soil Survey Staff (1975) defines the fermentation layer as 'a master organic horizon mostly characterized by disintegrated plant tissues in which partial macroscopically discernable vegetative structures

are dominant'. Materials composing this layer may be identified as to their origin, however, macromorphological decomposition is evident.

The humus layer lies directly above the uppermost mineral horizon and below the litter and fermentation layers. The Soil Survey Staff (1975) defines the humus layer as 'a terrestrial master organic horizon dominated by fine substances in which the original structures are macroscopically indiscernible'. The humus layer may be composed entirely of organic materials, or a mixture of mineral and organic materials. The humus layer is noted for its inherent variability in thickness and texture (Klinka et al., 1981).

For the purpose of this study, duff consists of three layers Oi (litter layer), Oe (fermentation layer), and Oa (humus layer), as defined by the Soil Survey Staff (1992). The Oi layer is composed of slightly decomposed organic matter, while the Oe and Oa layers consist of intermediate and highly decomposed organic matter, as previously stated.

Although numerous studies investigating evaporative drying rates of organic material have been performed, research efforts pertaining to rewetting are few and conflicting. Stocks (1970) observed that relatively dry duff absorbed more precipitation than wetter duff. However, Van Wagner (1965) reported that organic materials with low moisture contents do not absorb as much moisture as duff with a

higher moisture content. The mechanics of absorption were thought to be inhibited by the hydrophobicity of the substrate.

Fosberg (1977) reported very high and variable hydraulic conductivity in duff and speculated that duff moisture changes were regulated by the sorption properties of organic materials. This has led to a general assumption that wetting of duff is a function of both the total amount of rain and the duration of the wetting event. The visually obvious physical differences between fine- and coarse-needle conifer duff have similarly led to speculation that wetting is a function of duff type. Dry duff is reputed to be hydrophobic, thus rain retention should be a function of initial moisture content. Finally, the thickness of duff is an obvious variable influencing moisture storage capacity.

This study has several objectives. First, and foremost, is the construction of model which predicts post-storm duff gravimetric moisture content. From the collected data, moisture retention analyses with reference to storm characteristics, needle size, initial moisture content, and duff thickness will be conducted. A second model, using commercial peat moss in place of duff will be constructed.

A set of driving variables, generally thought to contribute to rewetting efficiency, were identified as model inputs. Independent characteristics identified for study were initial gravimetric moisture content, organic horizon

depth, storm duration, and delivered water depth.

METHODS

Sample Size Determination

Space and time limitations dictated that the $n = t^2s^2/a^2$ formula was not appropriate for determining sample size. A maximum of 35 monoliths could be handled by the rain simulator. As a result of time constraints, each storm was performed a set number of times (5).

Field Methods

Duff samples were collected in a stratified manner from forest stands of the southern Lolo National Forest. Cover types were categorized by the dominant overstory species and included: lodgepole pine (Pinus contora), ponderosa pine (Pinus ponderosa), western red cedar (Thuja plicata), grand fir (Abies grandis), sub-alpine fir (Abies lasiocarpa), western larch (Larix occidentalis), and Douglas-fir (Pseudotsuga menziesii). Detailed sampling data is found in Appendix 1.

Field sampling was concentrated in topographically mesic (mid-slope) areas that tended to contain typical moisture conditions and therefore, typical vegetation and organic matter deposition (Potts, et al., 1986). The duff

thicknesses of the sample population were compared against a previously cataloged set of species dependent duff thicknesses (Brown and See, 1981) to determine if the experimental population was representative of typical forest duff depths.

The monoliths were carefully removed with the vertical stratification of the organic horizon intact. The samples were prepared by removing as much mineral soil as possible from the organic horizon-mineral soil interface. The mineral particles, as a result of their physical properties, may otherwise have contributed to erroneous moisture content measurements. The surface area of the monoliths was reduced and placed in 20.3 cm by 20.3 cm wire baskets. The reduction of monolith dimensions did not alter the thickness. Each basket contained a fine nylon mesh inlay which prevented the organic material loss during the laboratory procedures (Alexander, et al., 1981).

Laboratory Methods

An rain simulator was constructed using PVC tubing, liquid application nozzles, water pressure regulator, and a timer (Appendices 1, 2, 3, and 4). The nozzles were strategically placed to deliver uniform "rain" to the bench surface. Rain gauges were used during calibration both during simulator calibration and experimental runs. A number of designed

storms were simulated: the western Montana 1 hour-2 year event (0.5"), 1 hour-25 year event (0.9"), 6 hour-2 year event (1.2"), and 6 hour-25 year event; and 15 minute "cloudbursts" delivering 0.3", 0.5", and 0.7" of water.

Gravimetric moisture content was the dependent variable. It was preferred over the volumetric content due to its acceptance in the fire science arena. Also, and perhaps more importantly, volumetric moisture content was difficult to calculate because of the variability in duff bulk density.

Several potential significant factors including intra-storm intensity fluctuations, percent mineral matter, evaporation, and precipitation distribution could not be controlled by the experimental design. Intra-storm variability was outside of the capabilities of the rain simulator. Simulation of intra-storm variability, including characteristics such as varying droplet size, varying intensity, and intermittence, was not possible because of the lack of knowledge regarding this parameter as well as being outside the simulator capability. A pressure regulator was installed to keep the water in the overhead array at a constant pressure of 30 psi. The regulator was used to keep the intensity as constant as possible. Mineral material content of the duff samples was assumed to be 0 %. Much of the mineral material was mechanically removed during

sample preparation. Due to its relatively high bulk density, mineral material can influence moisture content and produce erroneous measurements. Samples were not ashed upon the completion of the study to determine the exact mineral material content of each monolith. Evaporation between cycles was not a factor since the time between wetting cycles was insufficient for significant moisture loss (Gardener and Hillel, 1962 and Van Wagner, 1982). The rainfall distribution and depth varied under the simulator ($9.93"/\text{hr} + 0.42"$ at $\alpha = 0.05$; 8.5% error in delivery depth). Due to the variability of the rainfall pattern, each sample was randomly repositioned for each simulation. Consequently, it was assumed that each sample was receiving the same amount of precipitation.

Duff initial gravimetric moisture content, duff thickness, storm duration, and the delivered precipitation depth were identified as model inputs. The variables were selected because of their suspected importance. Both duff depth and delivered water depth were measured in inches. Storm duration was measured in hours.

Previous studies (Stocks, 1970 and Van Wagner, 1965) arrived at conflicting conclusions pertaining the effects of initial moisture content on percent moisture retention. A high initial moisture content may indicate that less volume is available for potential water absorption than at lower initial moisture contents.

Duff thickness is important since thicker monoliths have larger volumes. As a function of its volume and surface area, thicker monoliths have the potential to absorb larger amounts of moisture than thinner samples.

On a per weight basis, duff has a higher surface area to volume ratio than woody material. It is suspected that as a result of greater surface area per unit volume, forest duff moisture retention is less sensitive to rain event duration.

Delivered water depth represents the amount of water the samples receive. The depth measurement is simple, reproducible in the field, and subsequently, volume and weight values can be derived.

The experimental procedure consisted of four components, pre-weighing, wetting, post-weighing, and ODW determination. A range of initial gravimetric moisture contents representative of forest floor conditions was desired. Samples were dried until they reached random moisture contents between 10% and 100%. This procedure created a range of initial moisture contents and provided a better representation of potential forest floor moisture conditions with a minimal number of storm simulations. To expedite the drying process, the samples were placed in an oven at 40°C for varying periods to achieve the desired moisture content range. Standard methods were used to determine oven-dried-weight and gravimetric moisture content (Ponto, 1972).

RESULTS AND DISCUSSION

Duff Rewetting Model

The regression model for predicting post-storm is:

$$\theta = 6.6807 + 0.8494 x_1 + 56.7051 x_2 + 11.7378 x_3 + 0.29 x_4$$

The model variables are:

θ = the post storm gravimetric moisture content

x_1 = pre-storm gravimetric moisture content

x_2 = depth of precipitation (in)

x_3 = duff thickness (in)

x_4 = storm duration (hrs)

Pre-storm moisture content and rain depth were the most influential variables, having t-values of 32.4 and 10.7, respectively (Table 3.1). Duff depth also significantly influenced the post-storm moisture content ($t = 5.77$). Duration was not significant ($t = 0.244$), and neither was the constant ($t = 1.177$).

Table 3.1. Statistical results of the post-storm duff moisture model.

VARIABLE	COEFFICIENT	STANDARD ERROR OF COEFFICIENT	t
x_1	0.85	0.03	32.42
x_2	56.71	5.30	10.70
x_3	11.74	2.10	5.60
x_4	0.29	1.19	0.22
constant	6.68	5.68	1.18
$r^2 = 0.80$			

Figure 3.1 illustrates the relationship between the observed moisture content and predicted moisture content. The model overestimated low range moisture contents and underestimated high range moisture contents. As moisture content increased, the degree of correlation between observed and predicted moisture content decreased. This trend is seen in Figure 3.2 where the residual values diverged as moisture content escalates. Model confidence limits ($\alpha = 0.05$) were very large. The 95% confidence interval was roughly 170%. The observed value associated with a predicted value of 150% could vary from 80 % to 250% (Figure 3.3) The extreme variability, illustrated by the residual plot, contributed to the large confidence range.

The variable nature of duff structure was the primary contributor to the high degree of variability and large coefficient confidence intervals associated with the moisture prediction model (Table 3.2). The model resolution may be increased by including bulk density as an input variable. The bulk density descriptor would quantify an additional physical duff characteristic which may reduce the model variability associated with the duff substrate.

Table 3.2. 95% confidence limits for the duff moisture content prediction model coefficients.

variable	coefficient	low confidence bound	high confidence bound
duration	0.29	-2.04	2.62
duff thickness	11.74	7.62	15.85
initial θ	0.85	0.80	0.90
precip (")	56.71	46.30	67.11
y intercept	6.68	-4.47	17.83

Figure 3.1. The relationship between the observed value and the value predicted by the duff model.

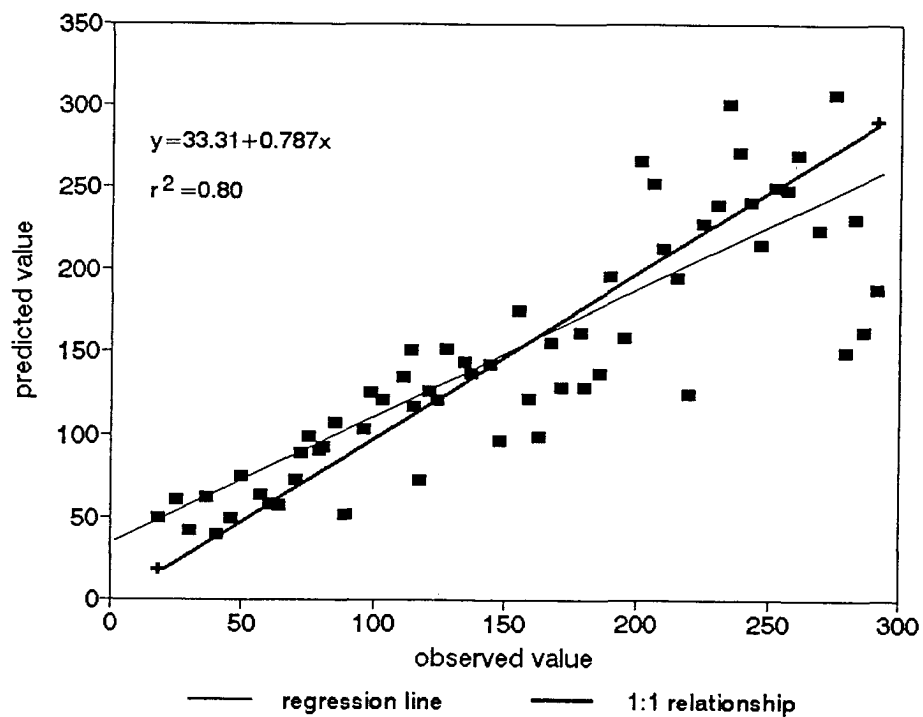


Figure 3.2. Duff moisture prediction model residual plot.

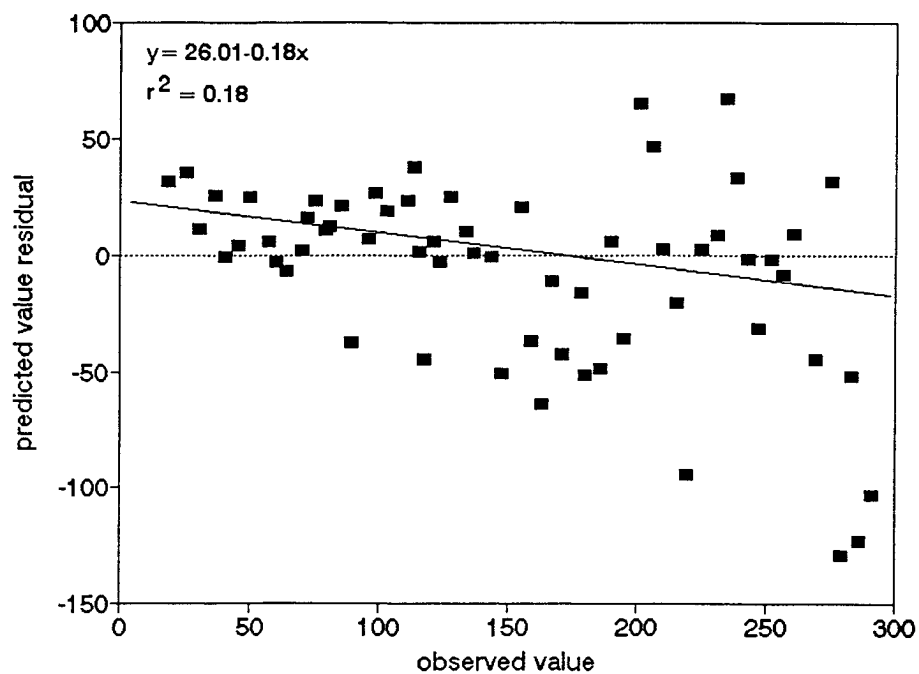
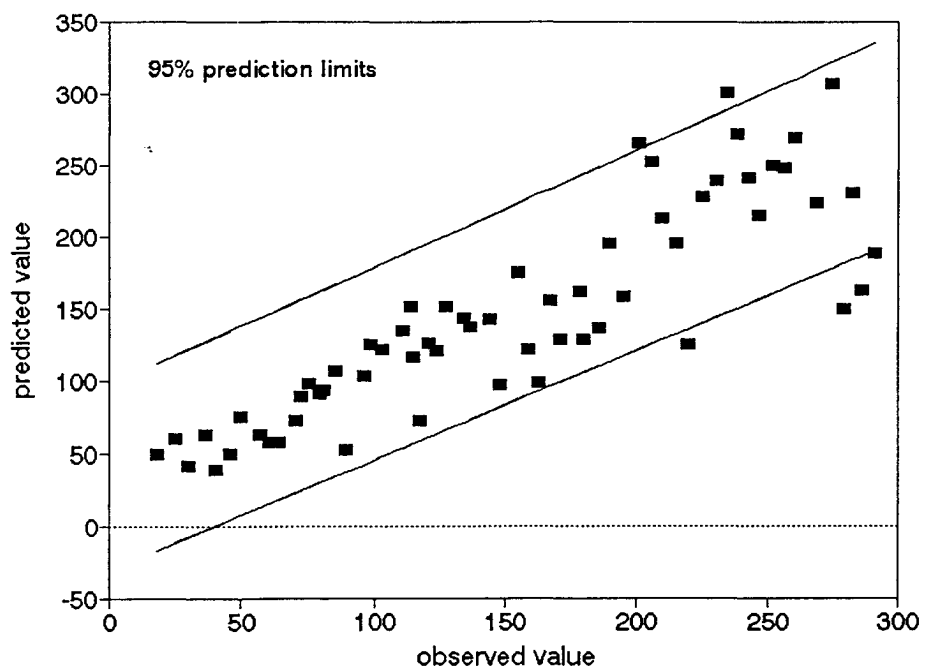


Figure 3.3. Prediction intervals ($\alpha = 0.05$).



Relation of Initial Moisture Content and Percent Retention

Percent moisture retention varies considerably based upon initial moisture content. The simulation runs were separated into four discrete storms. Table 3.4 shows linear regression results where the independent variable was initial moisture content and the dependent variable was percent retention. The null hypothesis states that the regression slope (β_1), for each storm, is equal to zero and there is no relationship between percent retention and initial moisture content.

Test: $H_0: \beta_1 = 0$

$H_0: \beta_1 \neq 0$

Test statistic:

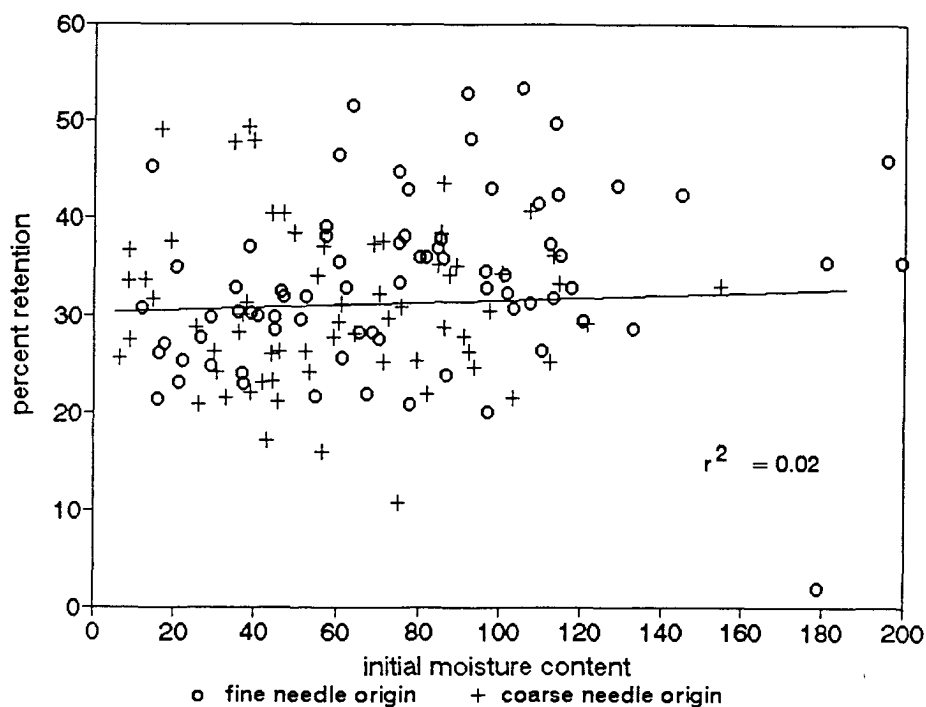
$$t = \beta_1 / s(\beta_1)$$

Table 3.3. Regression results of percent moisture retention (y) by initial moisture content (x).

storm	ppt	β_0	β_1	SE_{β_0}	SE_{β_1}	r^2	t
1 hr-2 yr	0.5"	30.09	0.033	8.38	0.02	0.02	1.70
1 hr-25 yr	0.9"	35.88	-0.063	8.69	0.01	0.18	-5.00
6 hr-2 yr	1.2"	25.72	-0.029	7.34	0.01	0.05	-2.64
6 hr-25 yr	1.8"	24.91	-0.055	7.70	0.01	0.20	-6.11

In the case of the 1 hour-2 year event, the null hypothesis was not rejected. The percent retention and initial moisture content relationship for the 1 hour-2 year event is shown in Figure 3.4. The data in Figure 3.4 was not similar to any of the common curve relationships. Further data transformations were not conducted. Initial moisture content did not significantly contribute to percent rainfall retention in the 0.5" storm.

Figure 3.4 Percent moisture retention with reference to initial moisture content for the 1 hour - 2 year storm event (0.5").

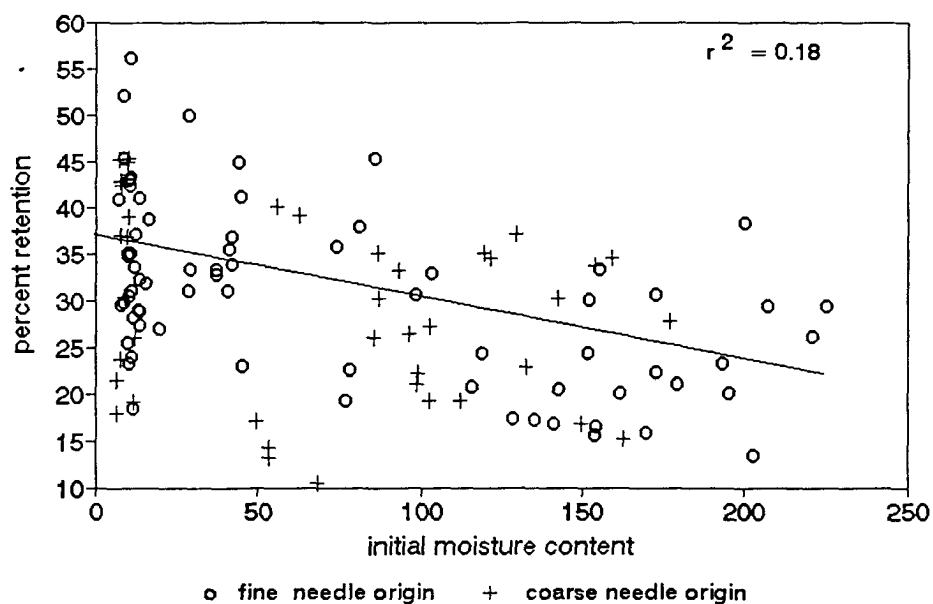


The null hypothesis was rejected for the 1 hour-25 year event. The relationship was:

$$y = 35.88 - 0.063(x)$$

where y was percent retention and x was initial moisture content. The r^2 value was only 0.18. The variability of duff depth was unaccounted for in this analysis and may contribute to the variability in the results and low correlation between the variables in each storm series. Figure 3.5 shows a downward trend in percent retention as initial moisture content increased.

Figure 3.5. Percent moisture retention with reference to initial moisture content for the 1 hour - 25 year event (0.9").

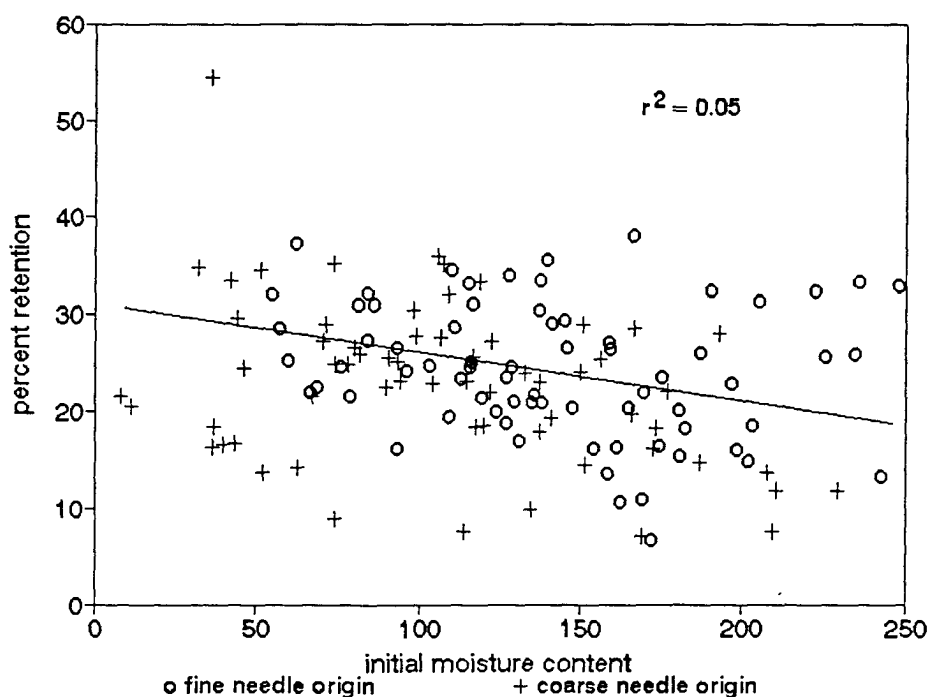


Under 6 hour-2 year storm conditions, the initial gravimetric moisture content significantly contributed to moisture retention, and the null hypothesis was rejected. The regression equation was determined by:

$$y = 25.72 - 0.29(x).$$

The downward trend in Figure 3.6 was not as strong as in Figure 5. The 1.2" event had fewer monoliths with initial moisture contents in the 0 - 25% range.

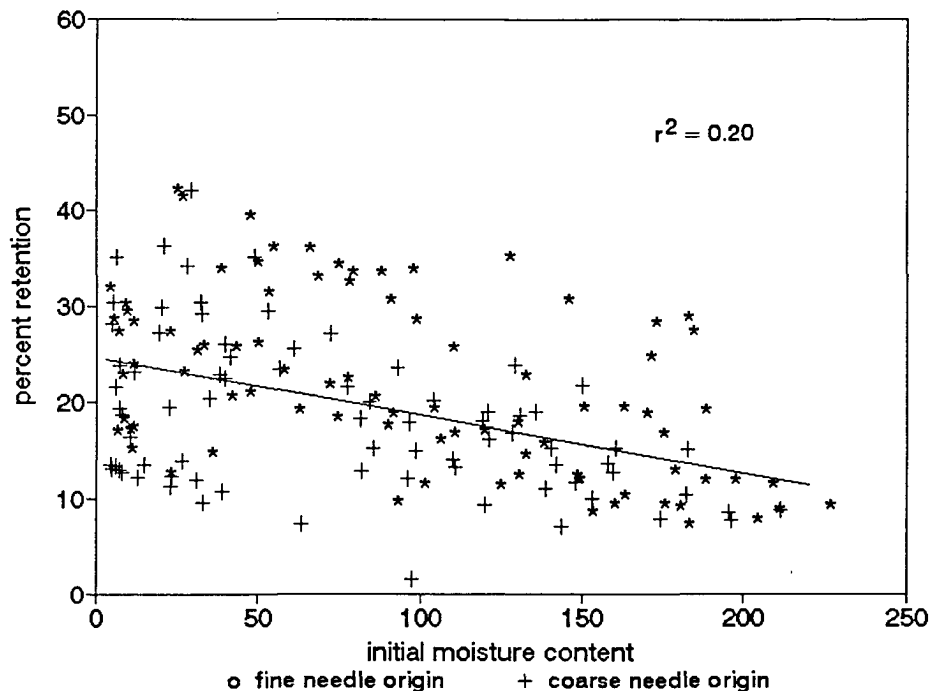
Figure 3.6. Percent retention with reference to initial moisture content for the 6 hour-2 year event (1.2").



The null hypothesis was rejected and the t-value was -6.11 for the 6 hour - 25 year event (Figure 3.7). The linear regression equation representing the relationship is:

$$y = 24.91 - 0.055(x).$$

Figure 3.7. Percent retention with reference to initial moisture content for the 6 hour - 25 year event (1.8").



This set of analyses illustrates a distinct qualitative relationship between initial moisture content and percent retention. The inherent variability of duff, coupled with monoliths of varying thicknesses, created considerable variability in the data which was evidenced by low degrees of correlation. Despite the low r^2 values in the regression analyses, the graphs revealed that in the 0.9", 1.2", and 1.8" storms a negative relationship between initial moisture content and percent retention existed. This characteristic was not discernable in the 0.5" storm. One half inch of precipitation was not sufficient enough to flood the monoliths and resulted in relatively higher moisture retention at higher moisture contents. Monoliths with moisture contents higher than 150 % did not retain as much water as monoliths with lower initial moisture contents during the three larger events.

Figures 3.8, 3.9, 3.10, and 3.11 delineate duff thickness, which will be discussed in detail in a later section. Despite the delineation by duff thickness, there were no consistent patterns of rewetability with reference to duff thickness. Enough graphical variability was evident that similar type regression analyses on the basis of duff thickness would likely be inconclusive. The 0 - 1" category typically had lower rewetability and lower initial moisture content than the other thicknesses. The consistently low initial moisture content was the result of the duff

preparation. A 1" thick sample dried more than a 3" sample when subjected to identical during conditions.

Figure 3.8. The initial moisture content, percent retention relationship is further delineated by duff thickness (1 hour - 2 year event).

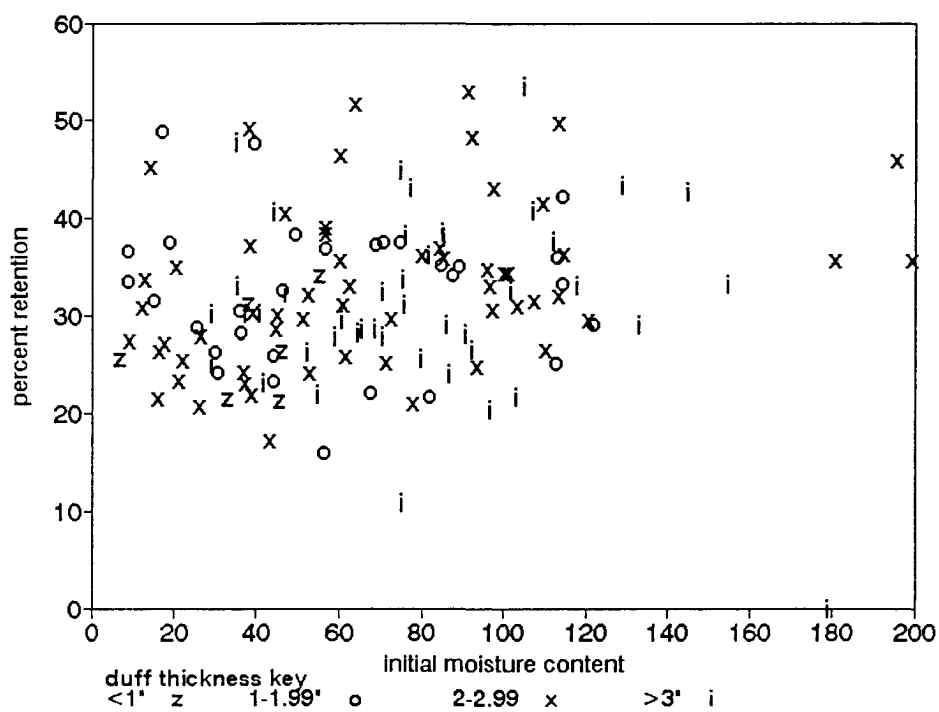


Figure 3.9. The initial moisture content, percent retention relationship is further delineated by duff thickness (1 hour - 25 year event).

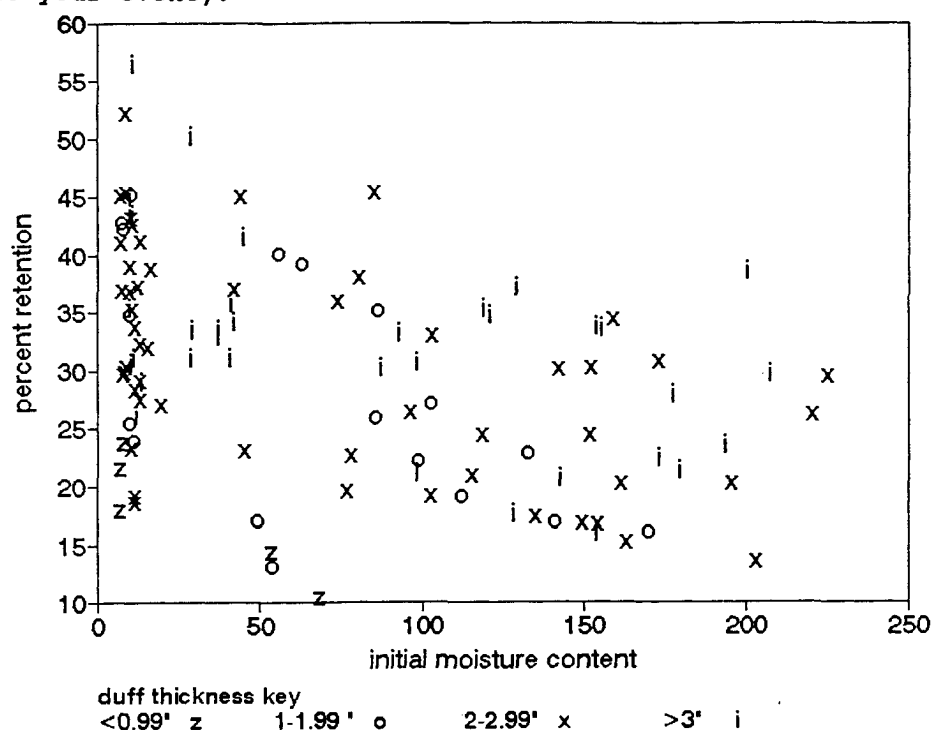


Figure 3.10. The initial moisture content, percent retention relationship is further delineated by duff thickness (6 hour - 2 year event).

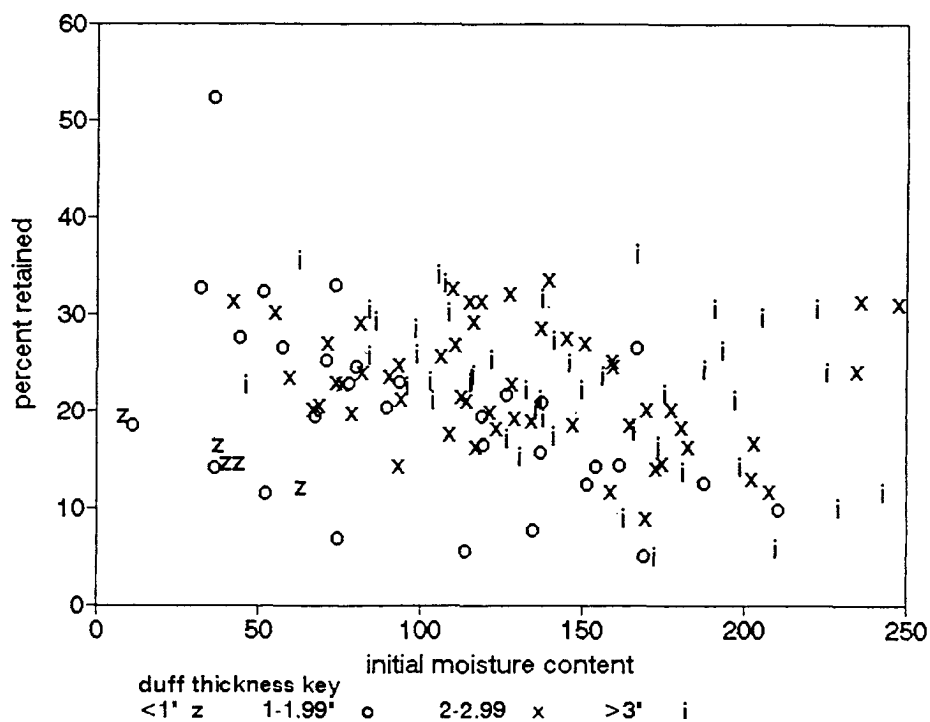
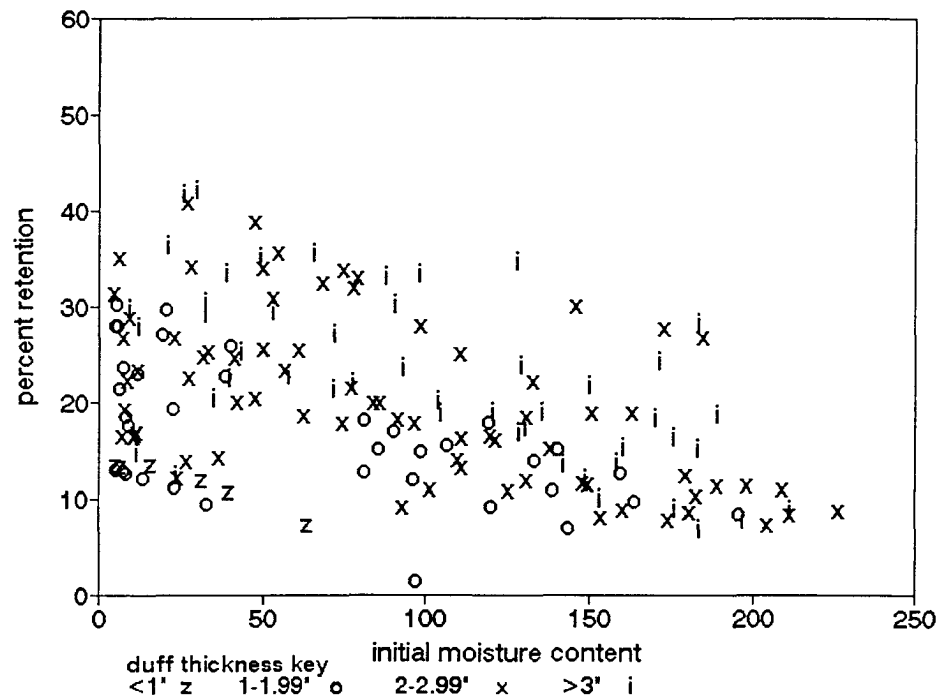


Figure 3.11. The initial moisture content, percent retention relationship is further delineated by duff thickness (6 hour - 25 year event)



Water weight gained by the monoliths under each storm setting is depicted by Figures 3.12, 3.13, 3.14, and 3.15. The trends are proportional to those characterizing initial moisture content and percent gain. Simulations which delivered larger precipitation depths resulted in the retention of larger weights and volumes ($1 \text{ g} = 1 \text{ cm}^3$) of water. A clear relationship was not evident in the 0.5" graph. However, the three larger storms illustrated large water gains made when the initial moisture content was small and the gains decreasing as the initial moisture content increased.

Figure 3.12. Weight gained with respect to initial moisture content (1 hour - 2 year event).

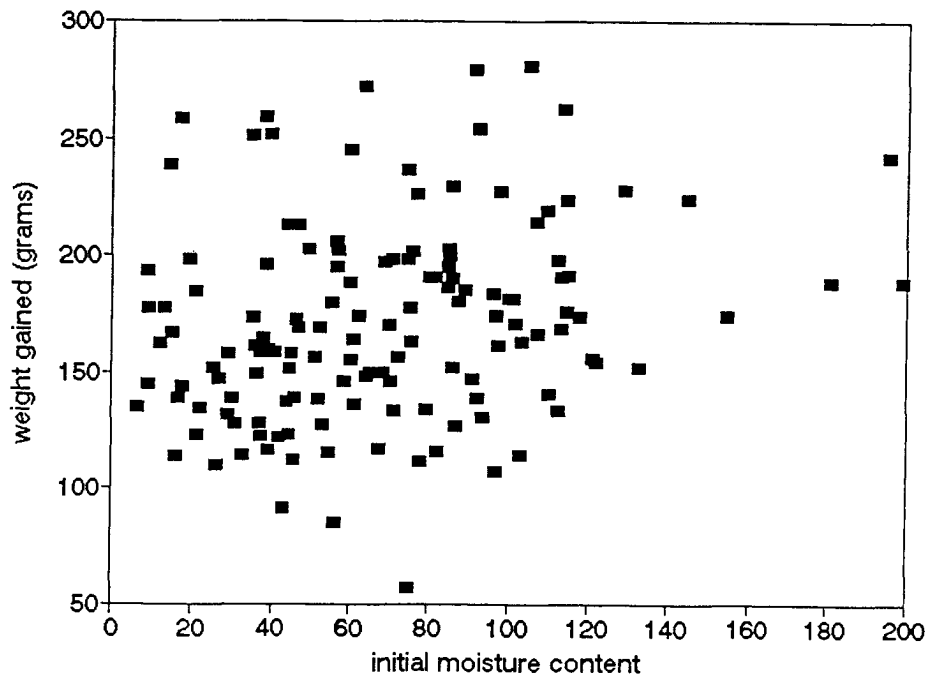


Figure 3.13. Weight gained with respect to initial moisture content (1 hour - 25 year event).

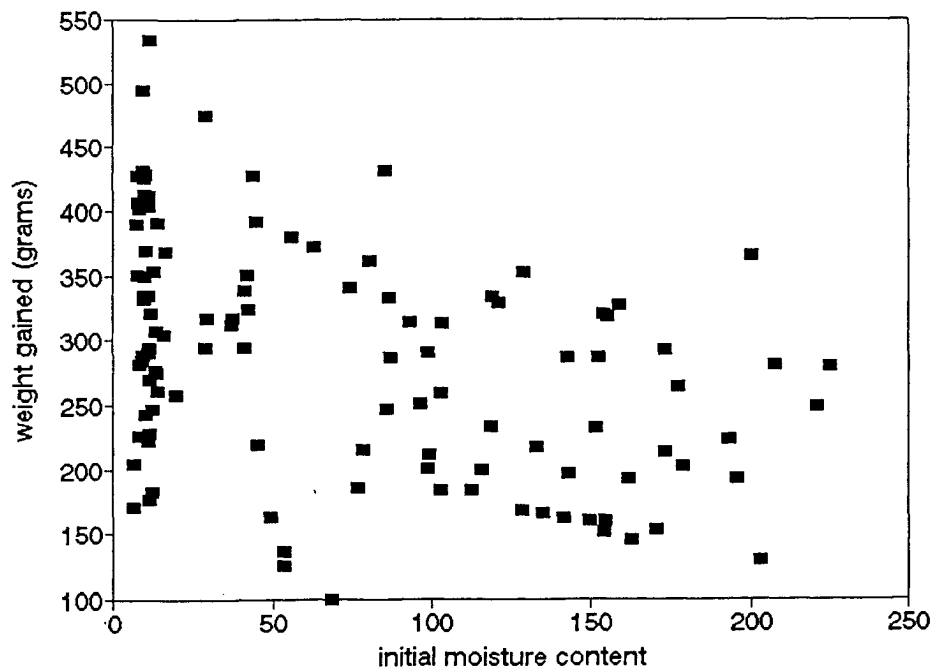


Figure 3.14. Weight gained with respect to initial moisture content (6 hour - 2 year event).

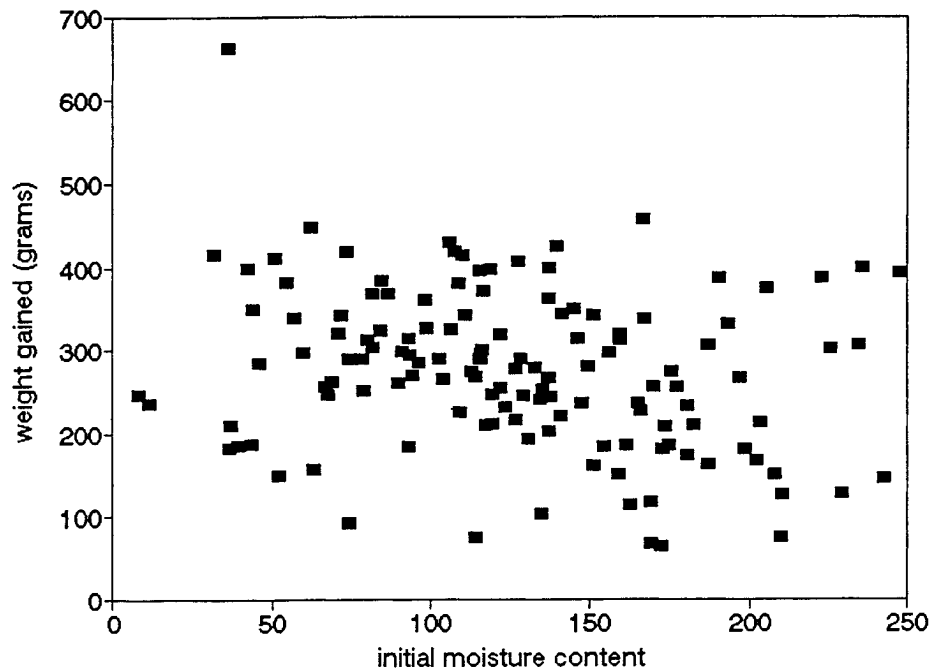
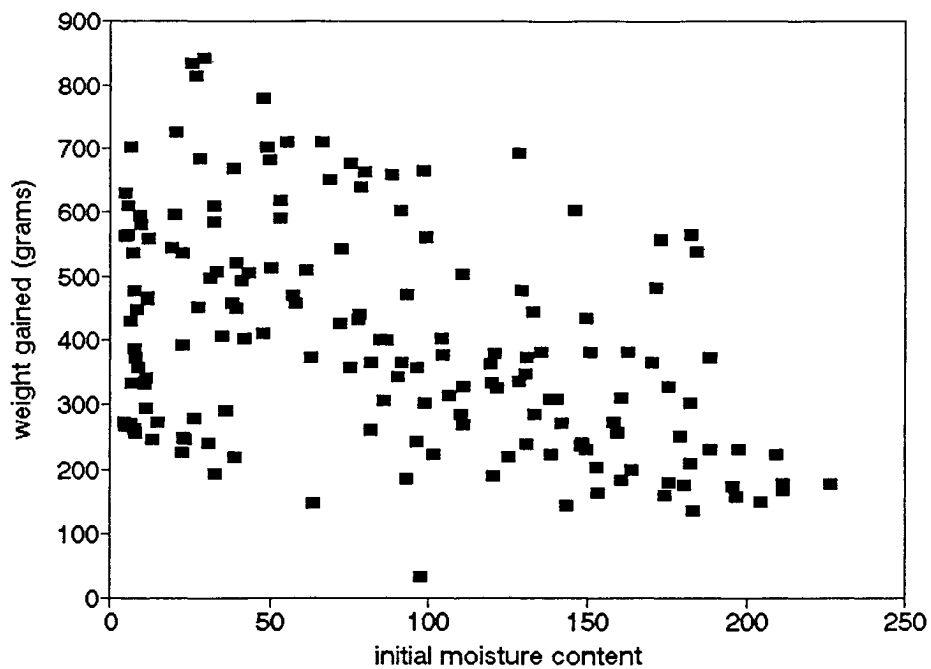


Figure 3.15. Weight gained with respect to initial moisture content (6 hour - 25 year event).



Influence of Precipitation Depth and Storm Duration on Moisture Retention

Precipitation was the second ranking, statistically significant element for predicting post storm moisture content. Moisture gain was positively related to precipitation depth (Figure 3.16). As water delivery increased, duff retained proportionally less moisture (Figure 3.17). Although more moisture was gained during heavier rain events, rewetting efficiency was lower.

Figure 3.16. Percent moisture retention delineated by storm depth.

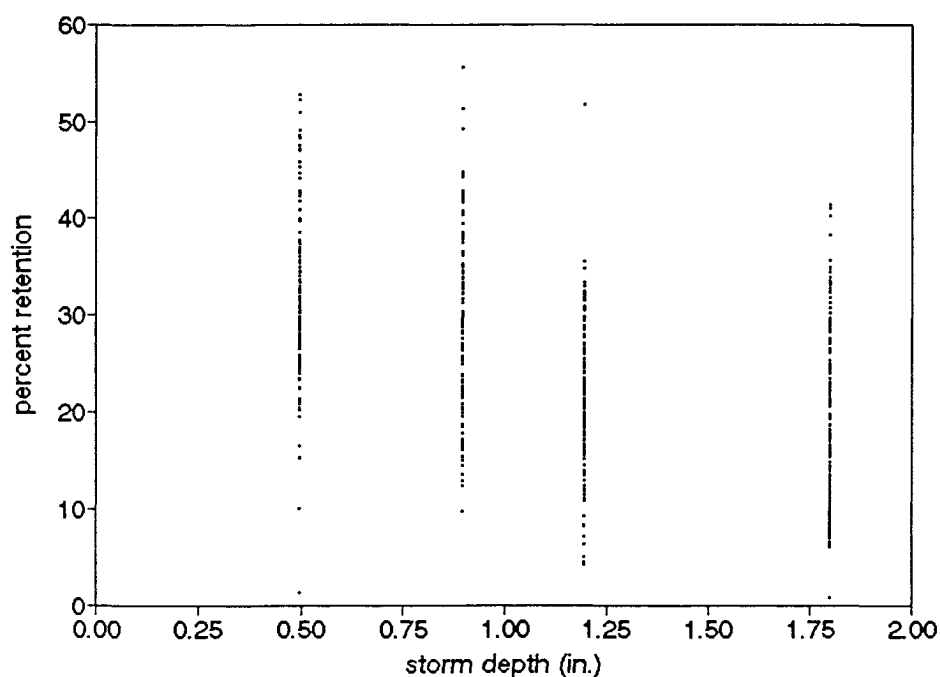
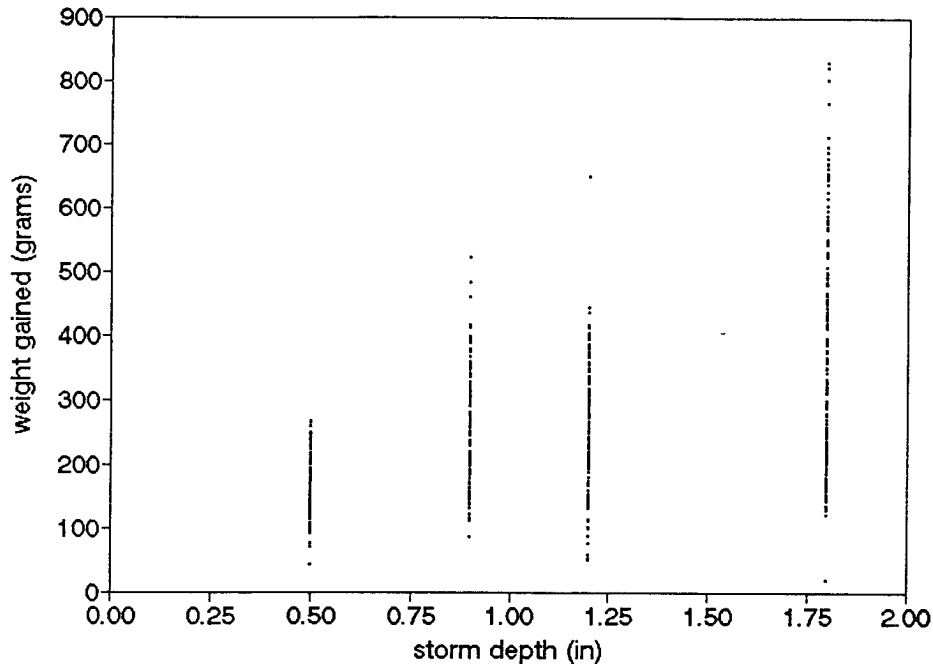


Figure 3.17. Duff weight gain delineated by storm depth.



It is possible that rewetting efficiency varied temporally throughout the storms. However, data support from this project was not available. Periodic weighing during rain events of constant intensity would provide an opportunity to investigate this question.

Mean percent retention, mean weight gain, and standard deviations for the monolith population with respect to each storm setting are presented in Table 4. The same monolith population (and therefore same distribution of duff depths) was used for each simulation. Also, the initial moisture contents were randomly arrived at by following a preset drying schedule. It can be assumed that with the exception

of the 6 hour-2 year event, which was skewed toward larger initial moisture contents, the distribution was similar throughout the complete storm simulation battery. The only unaccounted variable in the statistics calculated in Table 3.4 was duration, which was found to be statistically insignificant. In this particular experimental design, there was a correlation of 0.87 between precipitation depth and duration. This high degree of correlation resulted from longer storms delivering the larger precipitation depths. Fischer's Least Significant Difference methodology found no significant difference in mean retention between the 0.5" and 0.9" storm events. The mean retention similarity may be contributed to by lack of parity of initial moisture content values between the 1 hour-25 year and 6 hour-2 year monolith samples. The 6 hour-2 year event substrate generally had higher initial moisture content values. With initial moisture content being inversely related to percent retention, the 6 hour-2 year event sample retained less moisture than a monolith population with initial moisture contents having similar distribution in three of the storm sequences. There was no significant difference between the weight gain of the 0.9" and 1.2" events. The 171.6 g standard deviation for weight gain in the 6 hour - 25 year event is unexplained.

Concern that the selected storm sequences did not represent typical Montana rain events resulted in the

simulation of several "cloudburst events". The "cloudburst events" consisted of 15 minute storms delivering 0.3", 0.5, and 0.7" precipitation depths. The difference in duration did not effect percent retention or weight gain in the 0.5" event.

Table 3.4. Percent retention and weight gain means (x) and standard deviations (s) based on precipitation depths

depth (time)	percent retention		weight gain	
	x	s	x	s
0.5" (1 hour)	32.3 %	8.4	169.6	44.3
0.9" (1 hour)	30.3	9.6	286.7	90.6
1.2" (6 hour)	21.9	7.5	275.9	94.7
1.8" (6 hour)	19.8	8.6	395.4	171.6
0.3" (0.25 hour)	32.8	8.4	103.1	26.4
0.5" (0.25 hour)	31.3	7.4	164.1	37.6
0.7" (0.25 hour)	30.1	7.9	221.5	57.8

Relation of Moisture Retention and Needle Size

Needle size disparity was not found to be a substantial factor in moisture retention. The forest cover types were divided into two categories based on their needle size. Fine needle types consisted of short, slender needles that were associated with sub-alpine fir (Abies lasiocarpa), grand fir (Abies grandis), Douglas-fir (Pseudotsuga menziesii), and western larch (Larix occidentalis) cover types. The coarse needle category included lodgepole pine (Pinus contora) and ponderosa pine (Pinus ponderosa). Comparison was based on the assumption that the forest floor

cover derived from smaller materials contains more surface area over which moisture absorption may occur. The decomposed material in the humus layer should be of similar size regardless of its origin. Fine needle duff horizons (due to smaller size materials) have higher surface area to volume ratios than the litter layers.

Regression analyses were executed to determine if the percent retention-initial moisture content varied based on duff origin (Figures 3.1-3.4).

Regression analysis was used to test the following hypothesis:

$$H_0: \beta_c = \beta_f$$

$$H_0: \beta_c \neq \beta_f$$

where:

β_c is initial moisture content-percent retention slope of coarse origin monoliths and β_f the initial moisture content-percent retention of fine origin monoliths.

Linear regression results (Table 3.5) failed to consistently illustrate a significant difference in the retention patterns based on needle size. As in the earlier regression analyses, r^2 values were low (<0.28), indicating little correlation between variables. In both the 0.5" and 1.8" events there was a significant difference in percent

retention between the coarse and fine needled substrate and therefore, the null hypotheses were rejected. As a result of only four storm settings, it was not determined whether the results were random or if an undetectable trend was present.

Table 3.5. Result the percent moisture retention (y) by initial moisture content (x) regression based on coarse and fine needles.

storm	C/F	ppt	β_0	β_1	SE_{β_0}	SE_{β_1}	r^2	t
1 hr, 2 yr	c	0.5"	31.20	0.00	7.96	0.03	0.00	-2.02
	f	0.5"	30.43	0.04	8.59	0.24	0.04	
1 hr, 25 yr	c	0.9"	32.90	0.05	9.70	0.03	0.07	0.79
	f	0.9"	35.88	0.07	8.07	0.01	0.26	
6 hr, 2 yr	c	1.2"	27.47	0.08	7.82	0.02	0.12	1.06
	f	1.2"	22.55	0.02	6.64	0.01	0.04	
6 hr, 25 yr	c	1.8"	23.03	0.06	7.22	0.01	0.20	-2.01
	f	1.8"	21.07	0.06	7.63	0.01	0.28	

β_1 = coefficient
 β_0 = y intercept
 SE = standard error

As a result of the low regression correlation, a second analysis was conducted. The test was based on the earlier stated pretense that all variables were equal, except for the depth of precipitation delivered.

A two-sample t-test was used to test the following hypothesis:

$$H_0: x_c = x_f$$

$$H_0: x_c \neq x_f$$

where x_c is mean percent retention monoliths derived from coarse materials and x_f is mean percent retention of monolith derived from fine origins.

Two sample t-test statistic:

$$t = (x_1 - x_0) / ((s_1/n_1) + (s_0/n_0))^{0.5}$$

The mean percent retention of coarse and fine needle duff differed significantly after the 0.5 and 1.8" events thus, rejecting the null hypotheses (Table 3.6). This finding concurs with the results of the regression analysis. Fine needle duff has a higher percent retention in 50% of the storm settings.

Based on the accepted definitions of duff layers. The Oe and Oa layers in both needle types should have been subjected to similar degree of decomposition and humification. The primary physical difference is in the size of Oi layer materials. Coarse needle litter contains larger organic particles and therefore, less surface area per unit volume for potential absorption. Duff type, either by species or size, was not incorporated into the prediction model. The irregularity of the results indicated that this omission was acceptable.

Table 3.6. Mean percent retention and standard deviation based in needle size. Where \bar{x} is the mean moisture content and s is the standard deviation.

ppt(in)	\bar{x}_c	s_c	\bar{x}_r	s_r	t
0.5	30.82%	7.91	33.67%	8.70	-2.01
0.9	29.35	10.02	30.88	9.34	-0.78
1.2	21.17	8.30	22.55	6.74	-1.06
1.8	18.43	8.03	21.07	8.94	-2.02

Percent Retention, Weight Gain, and Duff Thickness

Figures 3.18 and 3.19 illustrate percent retention and weight gain based on duff thickness. Qualitative observation indicates that both weight gain and percent retention are positively influenced by duff thickness. The graphs indicate a high degree of variance within duff thickness groups, particularly the 6.3 cm (2.5") and 7.6 cm (3.0") thicknesses. Regression analyses were not pursued.

Figure 3.18. Effect of duff thickness on percent retention for the 1 hour, 25 year event (0.9").

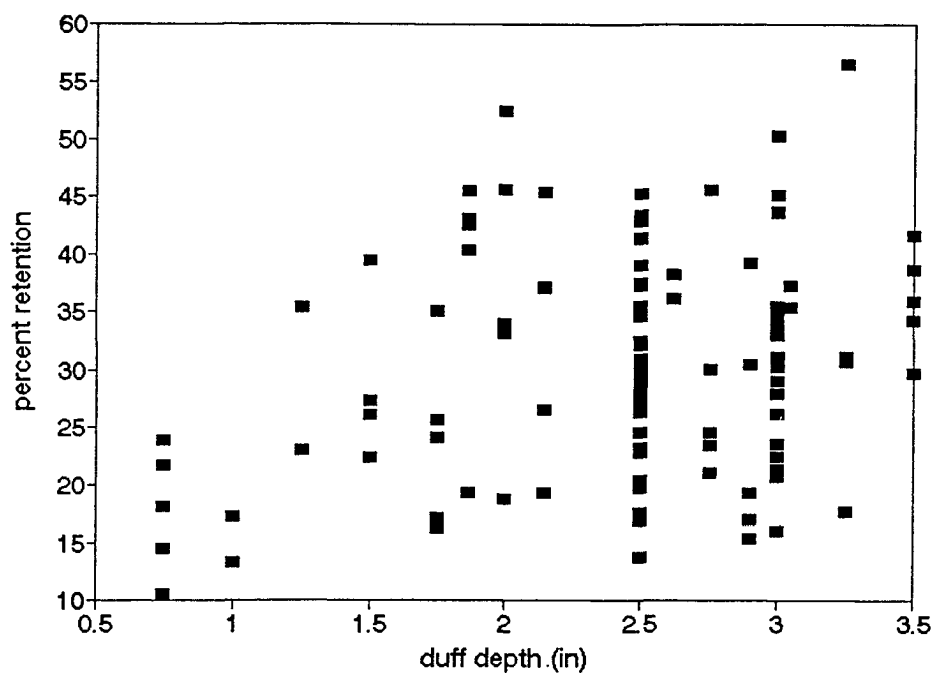
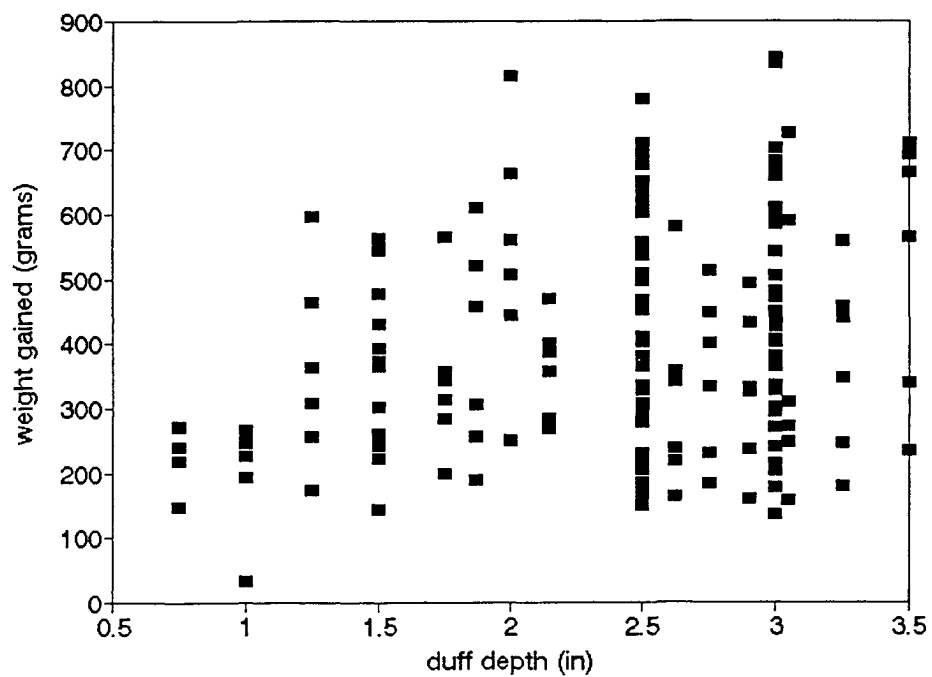


Figure 3.19. Effect of duff thickness on weight gained for the 6 hour - 25 year event (1.8").



An analysis of variance (ANOVA) was performed to determine if, with respect to percent retention, the variability between duff thickness exceeded the variability within thicknesses classes. Duff thicknesses were divided into four classes bases in the integer of their thickness. Thus, 2.5" would be "2", 1.3" would be "1", and so on. Table 3.7 contains the results of a one-way ANOVA and Tukey-B testing on the following hypothesis.

$$H_0: x_0 = x_1 = x_2 = x_3$$

$$H_1: x_0 \neq x_1 \neq x_2 \neq x_3$$

x_0 = mean percent retention for 0-0.99" thickness class

x_1 = mean percent retention for 1.0 - 1.99" class

x_2 = mean percent retention for 2.0 - 2.99" class

x_3 = mean percent retention for 3.0 - 3.99" class

Table 3.7. Analysis of variance.

Source	d.f.	sum of squares	mean squares	f ratio	f prob
between groups	3	2480.00	826.67	8.85	0.00
within groups	688	64279.51	93.43		
total	691	66759.51			

The probability of the f-ratio exceeding 8.85 by chance is 0.00. Thus, the null hypothesis was rejected. Mean percent retention varies depending on duff thickness. It is qualitatively evident that percent retention was positively correlated with duff thickness (Figure 3.19). Weight gain was directly proportional to percent retention. Therefore, mean weight gain based on duff thickness was not equal. The Tukey-B procedure, at $\alpha = 0.05$ level, found significant differences between the 0" class and all other groups and the 1" class and all other groups. A detectable difference was not found between the 2" and 3" classes.

Peat Moss Moisture Prediction Model

The response of commercial sphagnum peat moss to simulated rain was modeled using the methods and assumptions of the duff post-storm moisture prediction model. The model r^2 was 0.89.

The regression model predicting post-storm peat moisture content is:

$$\theta = 113.3872 + 0.7332x_1 + 137.0508x_2 - 72.6459x_3 + 8.1274x_4$$

where:

θ = the post storm gravimetric moisture content

x_1 = pre-storm gravimetric moisture content

x_2 = depth of precipitation (in.)

x_3 = peat thickness (in.)

x_4 = storm duration (hrs.)

The regression results contained several interesting features (Table 3.8). First, the initial moisture content was not as significant in the peat model ($t = 6.6$ compared to 32.42 for duff). Also, the y-intercept was significant. Third, and perhaps most interesting, was that β_3 (duff thickness coefficient) was negatively related to post storm moisture content. After the storm simulations only the top fraction (up to 0.25") of the peat was wet. The rest of the profile did not have any observable moisture differences. If only the top fraction of the peat profile was absorbing water, then thinner profiles would be more effective retainers of water than would thick profiles which had smaller fraction of their volume absorbing moisture.

Table 3.8. Statistical result of the peat rewetting model.

variable	coefficient	standard error of coefficient	t-value
initial moisture content	0.73	0.11	6.61
precip depth(")	137.05	28.83	4.75
peat thickness	-72.65	21.60	-3.36
storm duration	8.13	6.56	1.24
y intercept	113.39	40.58	2.80
$r^2 = 0.89$			

Table 3.9 illustrates 95% confidence limits for each coefficient and coefficients of variation for the peat and duff model coefficients. With the exception of duration and y-intercept, both of which were statistically insignificant in the duff rewetting model, the coefficients of variation were less in the duff model. The peat model had larger confidence intervals associated with each coefficient which attributed to a larger r^2 than the duff model.

Table 3.9. Confidence limits (cl) for the peat model coefficients, and coefficients of variation (cv) for both the peat and duff model coefficients

var	coefficient	low cl	high cl	CV (peat)	CV(duff)
duration	8.1274	-5.1170	21.3717	0.81	4.09
thickness	-72.6459	-116.2540	-29.0382	0.29	0.18
moisture cont.	0.7332	0.5092	0.9572	0.15	0.03
precip	137.0508	78.8331	195.2686	0.21	0.09
y int	113.3872	31.4316	195.3428	0.36	0.89

The correlation of observed moisture content to predicted moisture content was higher in the peat model ($r^2 = 0.89$), than in the duff model. The slope of the regression line was 0.89, which was considerably closer to a 1:1 ratio than the 0.78 of the duff (Figure 3.20). The greater uniformity

of the peat response may be the result of peat's marchohomogeneity. Residual values (Figure 3.21) were less uniform than in the duff model. The peat model tended to overestimate when observed moisture contents were less than 75%, underestimate between the observed values of 100% - 200%, and overestimate from 225% - 350%. The 95% confidence intervals for predicted values were large (Figure 3.22). A predicted value of 200 percent had a 95% confidence interval of 80% to 350%.

Figure 3.20. the relationship between the observed value and the value predicted by the model.

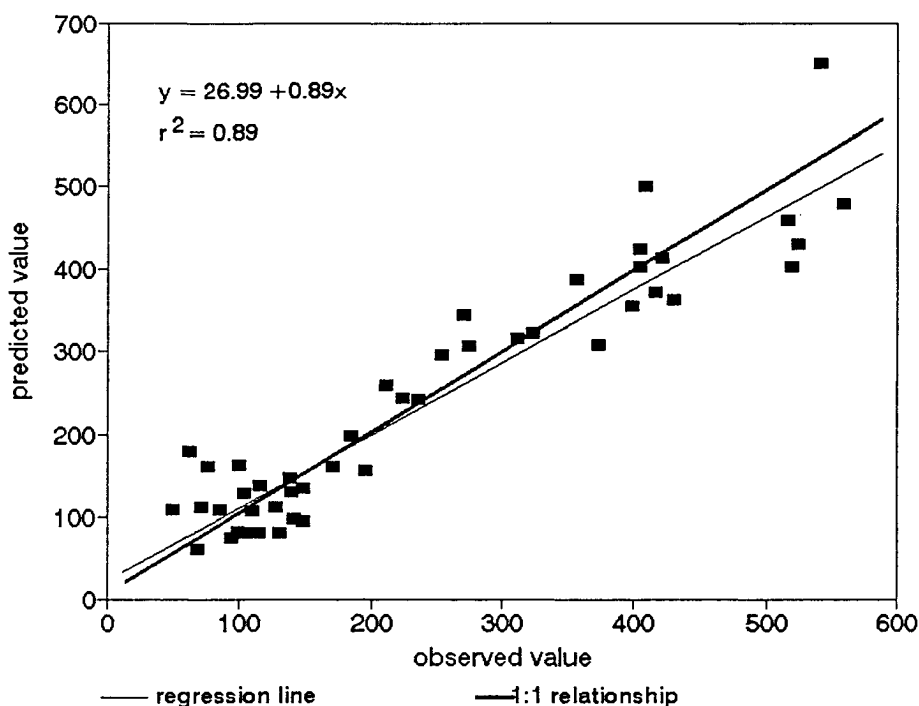


Figure 3.21. Prediction model residual plot.

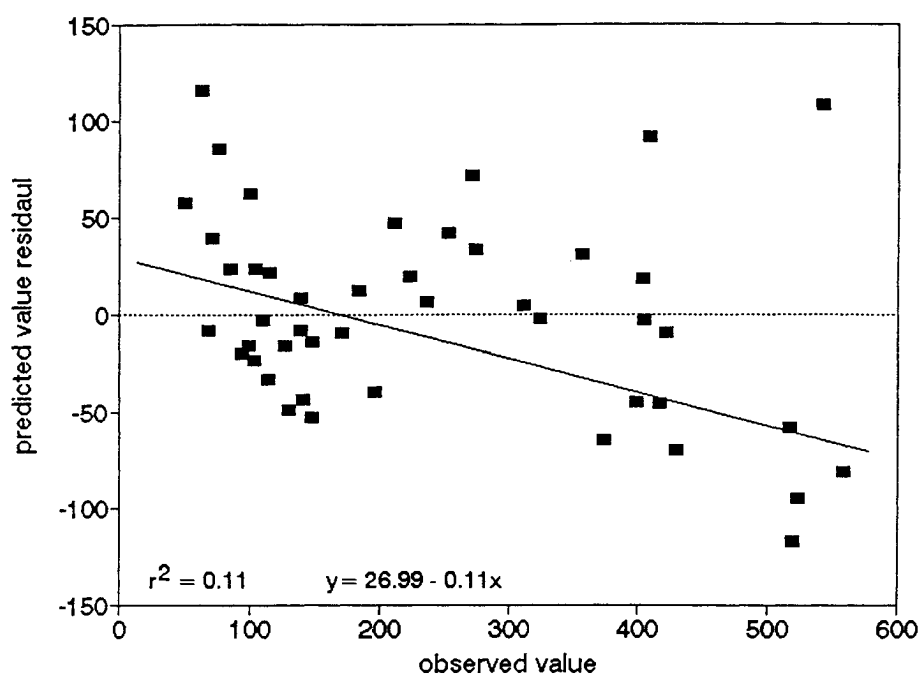
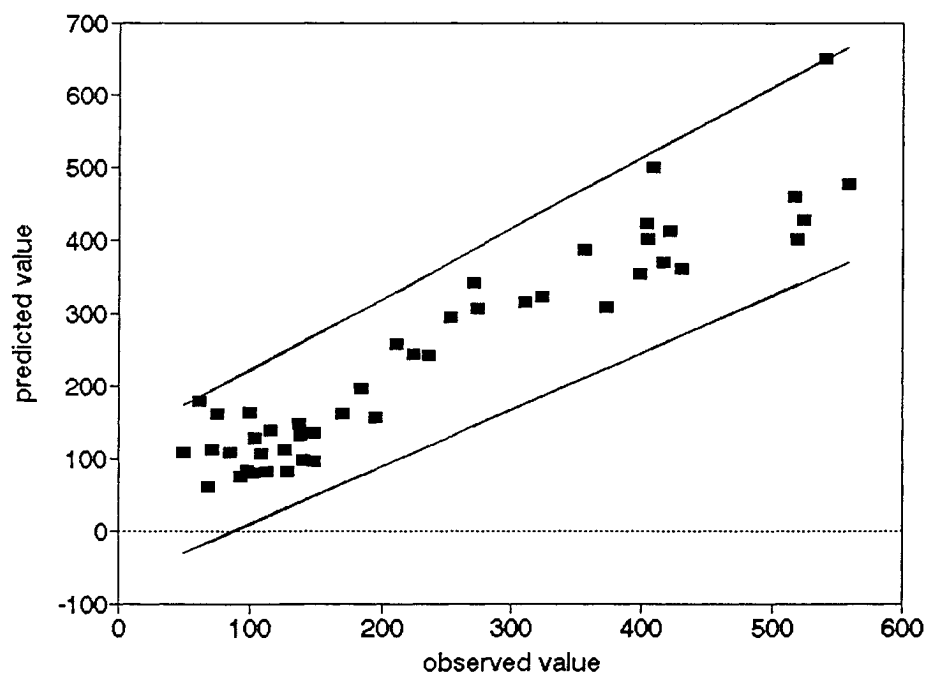


Figure 3.22. Prediction intervals ($\alpha = 0.05$).



CONCLUSIONS

The primary objective, model the rewetting efficiency of duff, was accomplished. Three of the four selected variables (initial moisture content, precipitation depth, and duff thickness) were highly correlated to the predicted moisture content. The confidence intervals were extremely large, about 170%. The large confidence interval limits practical model usage. Consideration and inclusion of model input error lessens model practicality. Adjustment of the driving variables to include duff bulk density could reduce inherent error resulting from the duff physical variability and improve model performance.

The peat model results were similar. In short, the confidence ranges were too large for practical application. The high degree of correlation between predicted and observed values was a function of the substrate's relative homogeneity. However, the results were somewhat misleading when considering the peat water absorption pattern, which did not emulate that of the duff monoliths.

Secondary studies illustrated that percent retention was inversely related to initial moisture content and precipitation depth. Percent retention was positively influenced by duff thickness. Water gain, by weight, was directly related to both duff thickness and precipitation depth. Under this experimental design, storm duration was found to be statistically insignificant.

The experiment was designed to construct a duff wetting model based on the four specified storms. This experimental design did not isolate single variables which hindered the analysis of each variables effect on percent retention. This project, as a result of both its complexity and design, leaves many doors open for future study. Work designed to improve the body of knowledge pertaining to physical duff characteristics and its moisture related behavior, both spatially and temporally is necessary.

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APPENDIX 1

Parts List: Overhead Array and Accessories

Overhead Array:

Number	Description
24	7" lengths of 1" PVC
3	3" lengths of 1" PVC
2	4' lengths of 1" PVC
1	2' length of 1" PVC
24	1" 45 degree PVC joints
24	1" 90 degree PVC street 'L's
24	1 " PVC bushings w/ .5" threads on inside surface
24	double males with .5" threads
24	.5" plastic nuts
24	Lurmark AN2.0 spray nozzles
26	1" PVC 'T'
1	1" PVC 'L'
3	1" PVC caps

Bench:

Number	Description
1	8' X 4' .75" exterior glue plywood sheet
2	8' 1" X 2"
2	4' 1" X 2"
	wood screws
0.33	yards of sand

Supporting Rack:

Number	Description
2	8' 2" X 2"
3	4' 2" X 2"
6	4.5" bolts with fitting screw and flat washers
4	2" wood screws w/eyes
9	large plumbing clamps
	light chain to hang the rack

Electrical and Flow equipment:

- 10 feet of .75" garden hose
- 1- .75" gated wye
- 1- 24 volt electronic valve
- appropriate electrical wire,tape, connectors, and contacts

100 volt to 24 volt transformer
waterproof container to house the transformer
chromatic sequence timer
surge protector
pressure regulator

APPENDIX 2

Rain Simulator Description

The overhead sprinkler system consisted of a series of Lurmark AN2.0 nozzles that were suspended 39" over a plywood surface. The simulator configuration was "E" shaped. The main stem of the stem was 108" long. Three 1" PVC branches, each 48" apart, were connected to the main stem. Each stem had 7 nozzles. The nozzles were connected to the branch in the following fashion: The nozzle was screwed into a .5" bushing which was cemented into a 90 degree street L. The street L was cemented to a 45 degree joint cemented into a 6" piece of 1" PVC which was connected to the branch. Attaching the nozzles to the branch in this manner elevated the nozzle above the branch and eliminated dripping when the system contained water not under pressure.

The system was calibrated to deliver a uniform amount of moisture at 30 pound per square inch (psi). To maintain constant pressure, a water pressure regulator was connected directly to a water source, which in this case was a garden spigot. A 10 foot piece of nylon hose was connected to a 12 volt electronic valve which was connected directly to the main branch of the overhead array. The electronic valve was wired to a 100 volt to 12 volt transformer. The transformer was connected to a chromatic sequence timer which controlled the

duration of the showers which composed one rainfall event.

A 4 ft by 8 ft piece of exterior glue plywood, which the duff samples were placed on, was positioned beneath the array at a slope of 3 degrees. The plywood was covered with a layer of coarse sand for drainage.

Design was influenced by Bodmer (1992), Bubenzer (1979), Neff (1979), and Peterson and Bubenzer (1986).

APPENDIX 3**Storm Sequence information:**

Event	Time(hr)	Depth(")	No. Sequences	Duration	Freq.
2 yr	1	0.5	4	21 sec	15 min
25 yr	1	0.9	4	43 sec	15 min
2 yr	6	1.2	12	14 sec	30 min
25 yr	6	1.8	12	25 sec	30 min
	0.25	0.3	3	15 sec	6 min
	0.25	0.5	3	28 sec	6 min
	0.25	0.7	3	43 sec	6 min

APPENDIX 4

Calibration Information

1) Variability reduction began with the individual nozzles. Of the thirty nozzles that were available for use, the twenty four which discharged the most uniform volume of water were selected. The one minute discharge of each nozzle was recorded three times. The mean discharge for each was then calculated and the population compared. Since no outliers were present, the population was reduced to twenty-four robustly by removing the three nozzles with the highest discharge and the three with the lowest discharge. The remaining nozzles were randomly incorporated into the array.

2) The bench was divided into 1 foot (ft.) by 1 ft. squares. The volume of water received by each area during one hour of continuous running at 30 psi was estimated by multiplying the average volume received in three five minute durations and multiplying by 12. The same procedure was repeated with areas that were 36 in² to achieve greater resolution of variance. The data were used to determine average intensity. The average intensity measure was used to determine the on/off cycle of the simulator.

3) The simulator was recalibrated for each storm to insure that the correct water volume was delivered. Rain gauges were strategically placed during each storm run to check simulator performance.

APPENDIX 5**Duff Monolith Collection Data**

Site	Location	Cover type	No.
1	T16N R38W S17	PIPO, PSME	8
2	T16N R23W S13	LAOC, THPL	4
3	T17N R24W S33	ABGR	4
4	T11N R22W S3	LAOC	6
5	T11N R22W S3	PSME	4
6	T11N R22W S3	ABLA	5
7	T11N R22W	PICO	4
8	T11N R22W	PICO	6
9	T18N R15W 27	PIPO	4